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RESEARCH AND DEVELOPMENT OF ADVANCED ROTORCRAFT CONCEPTS

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RESEARCH AND DEVELOPMENT OF ADVANCED ROTORCRAFT CONCEPTS*

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ABSTRACT

Research and development programs at Sikorsky Aircraft are described for several advanced rotary wing VTOL concepts. This includes the compound helicopter, with a wing and auxiliary propulsion, which has been extensively flight tested to speeds above 200 knots and can be extended to about 300 knots. Another development is a coaxial rigid rotor system which achieves excellent high speed performance by virtue of utilizing the high lifting potential on the advancing blades of each rotor. For highest speeds the tilting and stowed rotor concepts are being explored, and a unique variable diameter rotor system is under development.

INTRODUCTION

The high power per unit weight of the modern turbine engine has made possible many forms of vertically rising aircraft. The pure turbojet engine may be used to provide hovering lift directly, or a thrust augmentation system may be used to increase lift above that available from a given basic engine. In the latter instance the turbojet is used in most cases as a gas generator to drive a power turbine, which in turn drives a secondary fan to provide an increased mass flow through the overall system. The larger mass flow, accelerated to a relatively small vertical velocity, provides more lift than the small mass flow and high velocity of the basic turbojet. If the bypass ratio (ratio of secondary to primary mass flow) is on the order of 10 or less, the combination is usually arranged with concentric shafts and is labeled a turbofan. Much higher bypass ratios can be achieved, however. This usually is accomplished with non-concentric geometric arrangements with mechanical gear reduction to couple a high rpm turbine with a lower rpm fan, propeller, or rotor. In order of increasing bypass ratio, corresponding to a descending order of disk loading, are the turbofan, lift fan, ducted fan or propeller, conventional propeller, and helicopter rotor. The "bypass ratio" of the helicopter can vary from approximately two hundred to as much as one thousand.

High bypass ratios and low disk loadings offer a number of important advantages that derive from fundamental physics. The total thrust per unit gas generator power is high, so that the installed engine power requirement for a given gross weight is low. The corresponding fuel consumption per unit thrust is also low so that extended hovering times become possible . Downwash velocities and total slipstream kinetic energy per unit thrust are low, so that downwash impingement problems are minimized. Noise levels are also greatly reduced so that annoyance and detectability are substantially decreased. These basic factors are discussed in Reference 1.

Because of the beneficial features of high bypass ratio and low disk loading, and because of an extensive and successful background of helicopter development, it is quite natural that Sikorsky Aircraft continue to emphasize rotary wing concepts in advanced research and development. The pure helicopter, which for a quarter century was the only truly successful VTOL aircraft, continues to be developed and improved. Because of certain inherent speed limitations, however, there are several other rotary wing types in the research and development cycle at Sikorsky which will allow substantial increases in speed and productivity compared with current production helicopters. This paper will describe some of these concepts and discuss their development status.

ROTOR PERFORMANCE LIMITATIONS

The lifting capability of a helicopter rotor is lower in forward flight than in hover and decreases steadily with increasing forward speeds. The cause of this characteristic is the difference in velocities relative to the blades on the "advancing" and "retreating" halves of the rotor disk, which results in a very large dissymmetry in local dynamic pressures. No conventional rotor system is able to support large rolling moments, either because of flapping hinges or because of limited capacity of the blade structure, rotor head, or shaft to withstand large vibratory bending moments. For single rotor helicopters, the rolling moment must be essentially zero in any case due to lateral trim requirements. Consequently the large dynamic pressures on the advancing side of the rotor cannot be utilized and advancing blade lift must be reduced to approximately the level of the retreating blade lift, the maximum value of which decreases rapidly with increasing forward speed.

To illustrate the above elementary considerations, the reduction in size of the operating envelope of a typical helicopter rotor with increasing forward speed is presented in Figure 1. Rotor lift is plotted vertically against propulsive force (or drag) on the horizontal scale; thus a line from the origin to any point on the graph represents the rotor resultant force vector for that point. The operating limits for a given forward speed are retreating blade stall and a line corresponding to autorotation (zero power). The stall line represents a moderate retreating blade stall condition.

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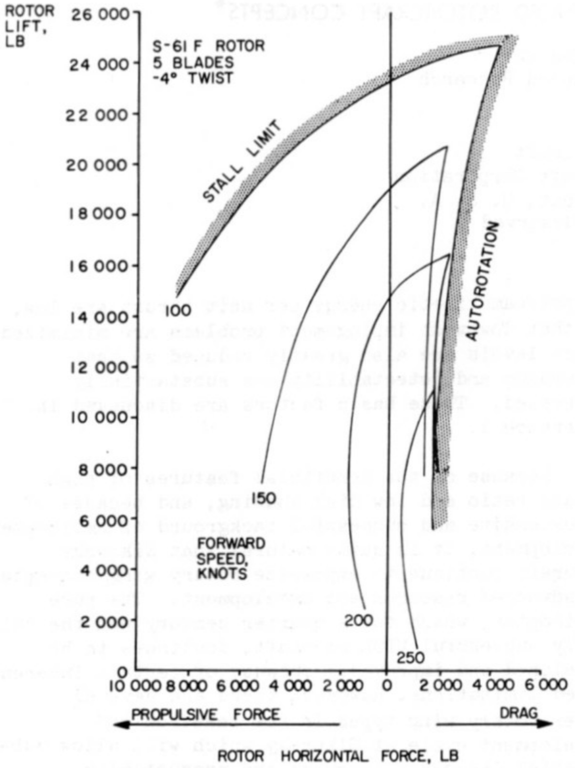

FIGURE 1. EFFECT OF FORWARD SPEED ON OPERATING ENVELOPE.

Operation above or to the left of this line is possible but at the expense of rapidly deteriorating efficiency and increasing vibration. Operation to the left of the autorotation line requires a power input to the rotor. Operation to the right of the autorotation line is not normally possible because the rotor is generally equipped with an overrunning clutch that precludes a negative torque condition. Within the two basic limits, the rotor may operate at any point except as may be restricted by less fundamental limits of available blade pitch, power, allowable stresses, flapping freedom, etc. As may be seen, the operating envelope shrinks rapidly with increasing forward speed. At 200 knots the maximum propulsive force is less than 20 percent that at 100 knots, although the parasite drag that must be overcome has increased by a factor of four. At 250 knots the propulsive force capacity has entirely vanished, with the rotor producing drag at all operating conditions. Thus it is clear that auxiliary propulsion is required for rotorcraft in the speed range above 200 knots; it is also clear that a wing, with inherently good aerodynamic efficiency and a lift capability that increases rapidly with forward speed, is a logical means of supplementing rotor lift at high speeds.

COMPOUND HELICOPTER

If the speed limitations of the conventional rotor system as discussed above are overcome by the addition of a wing and a separate propulsion system, the resulting configuration is commonly termed a compound helicopter. It has received more attention over a longer period of time than any other of the advanced configurations, and for this reason is closest to operational use. This configuration will be discussed first.

Performance Characteristics of a Wing-Rotor Combination

To illustrate the effects of adding a wing to a rotor system, in terms of lifting capability and lift-drag ratio, a representative example of such a combination lift system is presented. The assumed rotor system has a diameter of 72 feet, a solidity σ of 0.10, and zero blade twist. This rotor is appropriate to a compound helicopter having a gross weight of 40,000 lb. The corresponding disk loading is 10 pounds per square foot.

The variation of rotor tip speed with forward speed is shown in Figure 2. A constant value of 700 ft/sec is assumed at low speeds. At high forward speeds rotor tip speed is reduced such that the maximum local Mach number at the tip of the advancing blade, corresponding to the sum of forward speed and tip speed, is limited to a specified value. Two Mach number values, 0.8 and 0.9, are shown in Figure 2. Experience has indicated that a Mach number of 0.9 is approximately the maximum value that may be allowed without incurring a severe performance penalty, and, as will be shown, a lower value is desirable for best efficiency.

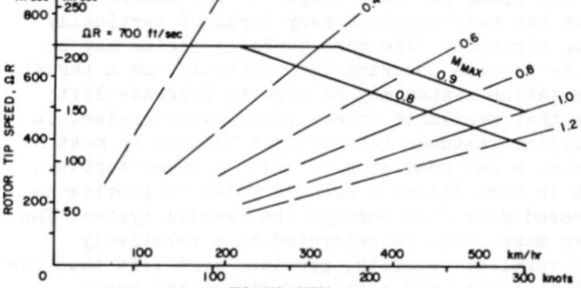

FIGURE 2. ROTOR TIP SPEED VARIATION

The lift capability of the rotor system for the assumed tip speeds is shown in Figure 3. The maximum rotor lift at any speed is defined as that corresponding to a moderate retreating blade stall condition (drag torque parameter $bC_{Qd} / \sigma = .004$ as described in Reference 2 and 3). In forward flight the same degree of blade stall can be encountered at various combinations of rotor lift and propulsive force, as indicated in Figure 1. The lift values shown in Figure 3 over most of the forward flight range are the peak values which occur at zero rotor power (autorotation), although this is not necessarily the optimum operating condition. Higher lifts than those shown are possible throughout the speed range, but only at the expense of substantially increasing rotor drag or power and increasing vibration levels. As may be seen, the assumed 40,000 pound gross weight aircraft would not be able to fly faster than approximately 140 knots at sea level with rotor lift alone, because of the decreasing lift capability with increasing forward speed. Auxiliary propulsion would be required to achieve even this speed with this particular rotor, which is not the design that would be used for a

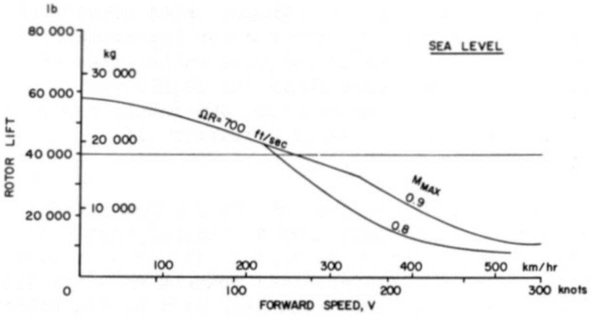

FIGURE 3. ROTOR LIFT CAPABILITY

pure helicopter. Note that the rotor lift capability drops off more sharply when the tip speed is reduced at high speeds. The lift for a maximum Mach number of 0.8 is much less than for a Mach number of 0.9. This difference in lift is due primarily to the reduction of local dynamic pressures felt by the rotor blades on both advancing and retreating halves of the disk at the lower tip speeds. The maximum useable section lift coefficients are lower at the high Mach number, but the magnitude of the local dynamic pressures is of greater significance.

The influence of a wing on overall lift capability is shown in Figure 4. The size of the assumed wing is 300 square feet, which is three-quarters of the total nominal rotor blade area ($\pi R^2\sigma$), and which provides a wing loading (gross weight/wing area) of approximately 130 pounds per square foot. The assumed aerodynamic characteristics provide a maximum lift-drag ratio of the isolated wing of 25 at a lift coefficient of 0.4. The lower of the two rotor lift curves of Figure 3 is reproduced in Figure 4 and was used in summing total lift. It may be seen that the maximum lifting capability including the wing increases rapidly with speed at a wing lift coefficient of 1.5. This value may be obtained without the use of flaps. Thus maximum load factor capability and/or altitude capability increases with speed, as opposed to the conventional pure helicopter. The data also show that a 40,000 pound gross weight aircraft can operate from hover up to a maximum speed as limited by available power without exceeding a wing lift coefficient of 0.6. The requirement for peak wing lift coefficient occurs in the vicinity of 200 knots flight speed.

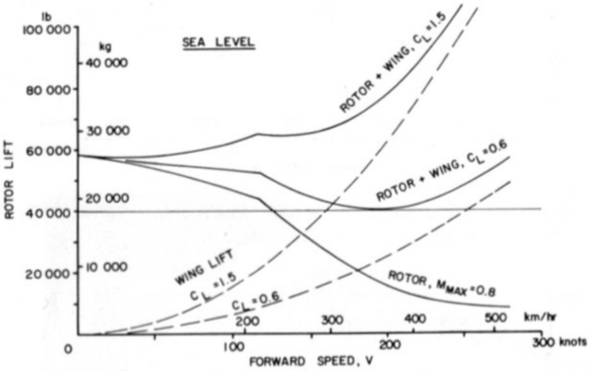

FIGURE 4. EFFECT OF WING ON LIFT CAPABILITY

To illustrate the benefits of a wing and a separate propulsion system on altitude capability, Figure 5 shows a typical result. The compound helicopter has a cruise speed capability which is a function primarily of installed horsepower. The installed power was chosen arbitrarily in this case to provide a 250 knot cruise speed potential at 10,000 feet. Because increasing altitude decreases available power and parasite drag in approximately the same proportions, cruise speed is nearly independent of altitude until wing lift coefficients become excessive. The pure helicopter, on the other hand, is blade-stall limited despite the fact that a higher solidity rotor was assumed than for the compound, so that maximum speed drops quite rapidly with increasing altitude. Thus the compound helicopter enjoys an increasing speed margin over the conventional helicopter as altitude increases, and is also able to operate at higher maximum altitudes.

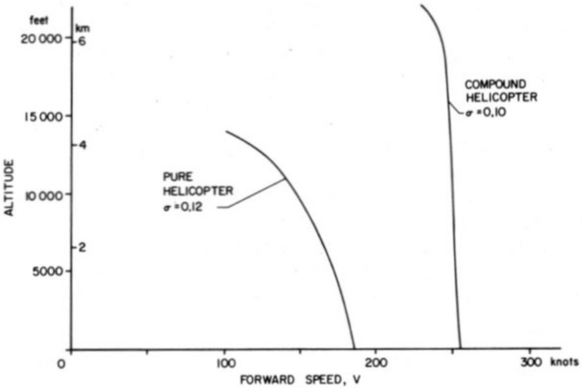

FIGURE 5. EFFECT OF ALTITUDE ON CRUISE SPEED

Lift-drag ratio in forward flight is a very important performance parameter, as it determines fuel consumption and installed power requirements for the aircraft in cruise. The lift-drag ratio of the rotor alone is presented in Figure 6 for the two advancing blade Mach number conditions. Lift-drag ratio of a rotor is defined as lift over equivalent drag, where the equivalent drag is equal to the actual rotor drag (which can be negative in a propulsive force condition) plus the ratio of the shaft power to the forward speed. In hover the lift-drag ratio as defined is zero, but increases with forward speed to a maximum value at approximately 175 knots for this rotor system. It may be seen that advancing tip Mach number is very important with regards to rotor cruise efficiency; a maximum

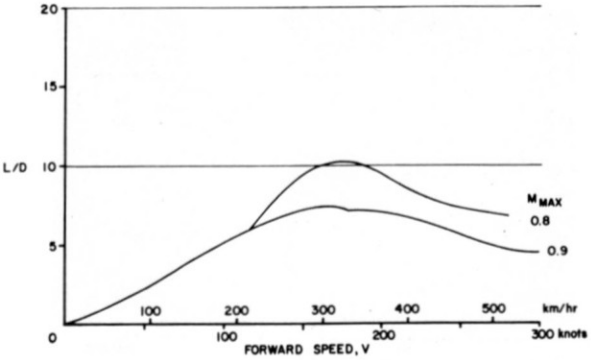

FIGURE 6. ROTOR LIFT-DRAG RATIOS

L/D of about 10 is achieved for an advancing tip Mach number of 0.8 compared to about 7 for the Mach number of 0.9 case. These numbers do not include a penalty for rotor head drag, which, of course, is inevitably present to some degree and will reduce the L/D values.

The effect on L/D of adding a wing is shown for the advancing tip Mach number of 0.9 case in Figure 7. In this figure the lift coefficient of the wing has been adjusted at each speed so that the combined wing and rotor lift is equal to the gross weight of 40,000 pounds. The lift-drag ratio of the wing is much higher than that of the rotor at high speeds so that the lift-drag ratio of the combination also increases with speed to a value greater than 10. The reason for the rapid drop in wing L/D at reduced speeds is two-fold. First, the wing lift requirement is low so that it is operating below the optimum lift coefficient, and second, it is operating within the downwash field of the rotor so that it suffers an interference drag effect. This interference effect diminishes rapidly with increasing forward speed and contributes less than 2 percent of the combined wing and rotor drag at 300 knots.

The effect of the wing on L/D for the 0.8 Mach number case is shown in Figure 8. Results are qualitatively similar to those of the previous figure, except that the lift-drag ratio of the wing-rotor combination is significantly improved, to values as high as 16 at the maximum speed considered. Also shown in Figure 8 is the further improvement to be obtained by cruising at altitude rather than at sea level. For the curve shown for 10,000 feet altitude, a slightly larger wing (400 square feet) was assumed in order to avoid excessive lift coefficients.

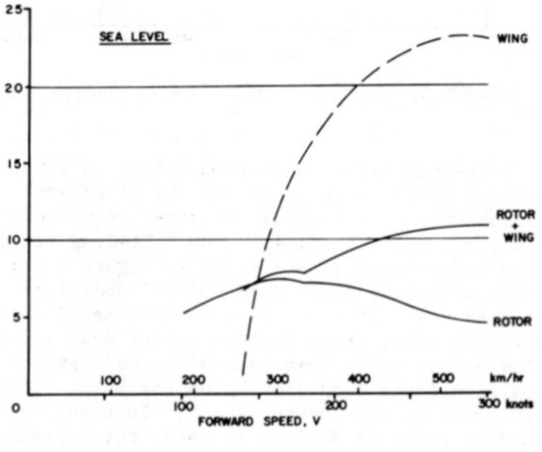

FIGURE 7. EFFECT OF WING ON LIFT DRAG RATIOS, ROTOR M_{max} = 0.9.

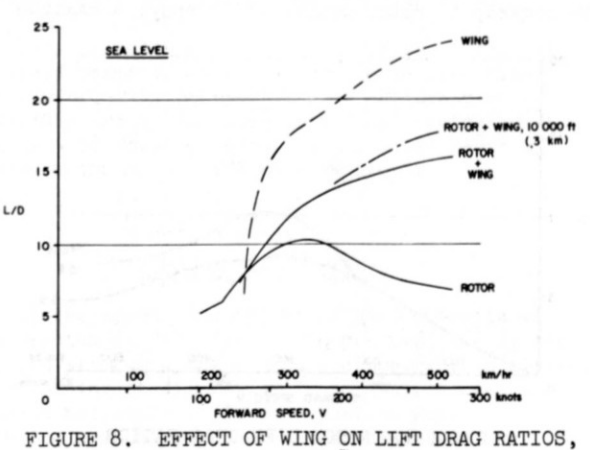

FIGURE 8. EFFECT OF WING ON LIFT DRAG RATIOS, ROTOR M_{max} = 0.8.

It should be noted that at the maximum speeds considered the rotor lift used in the calculations amounts to only about 20 percent of the gross weight. In fact, it may be desirable for reasons of vibration and blade stress to carry even less lift on the rotor. This will not influence the combined rotor-wing lift-drag ratio appreciably, however. Reducing rotor lift to zero, for example, will reduce the L/D from 16 at the maximum indicated speed (sea level case) to approximately 14.5.

As mentioned previously, the lift-drag ratios presented do not include a penalty for the parasite drag of the rotor head or pylon. It is not possible, of course, to avoid some kind of drag penalty. Accordingly, the influence of rotor head drag on the combined rotor-wing lift-drag ratios are presented in Figures 9 and 10 for sea level and 10,000 feet altitude, respectively. In each case three levels of parasite drag are shown as well as the zero drag condition. The highest value of parasite area, f (defined as drag force divided by dynamic pressure), of 15 square feet corresponds roughly to current production rotor heads for this weight category aircraft with no attempt at fairing. As may be seen, this drag characteristic results in a severe drop in overall lift system L/D values, particularly at high speeds

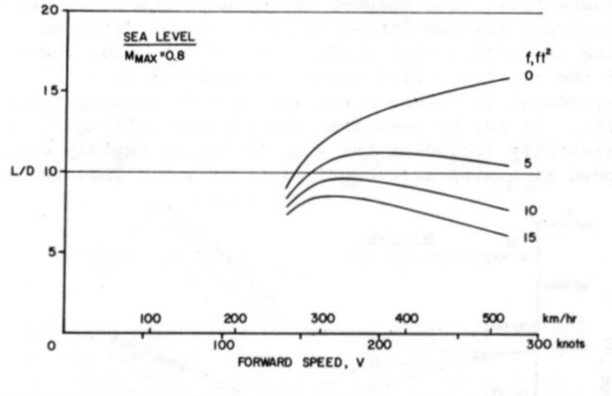

FIGURE 9. INFlUENCE OF ROTOR HEAD DRAG ON ROTOR-WING $L/_D$, SEA LEVEL.

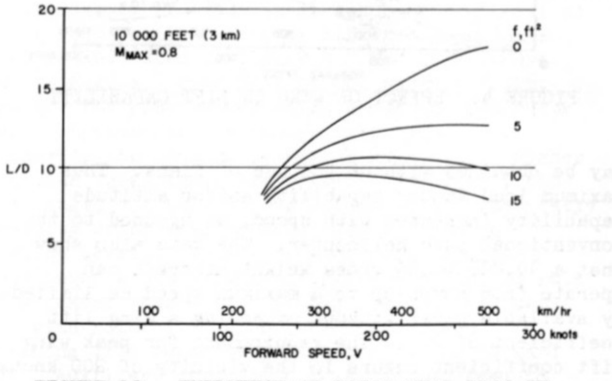

FIGURE 10. INFLUENCE OF ROTOR HEAD DRAG ON ROTOR-WING $L/_D$, 10,000 FT.

It is clear that reduction of rotor head drag is required to allow a compound helicopter to cruise efficiently at high speeds. If the lowest indicated value of rotor head parasite area can be achieved by proper design, then very respectable values of lift system cruise efficiency can be maintained out to forward speeds of 250 knots or higher, especially at altitude.

Compound Helicopter Research and Development

Sikorsky Aircraft has been actively engaged in research and development activities on the compound helicopter for more than a decade. Many of these activities were reported in Reference 4. One of the experimental research tools that has been utilized to a great extent in the past several years is a wind tunnel model of a generalized compound helicopter, shown in Figure 11. This model has been used in a number of investigations supported by the U. S. Army Aviation Materiel Laboratories (AVLABS). It has a four-bladed rotor 9 feet in diameter, with the blades dynamically scaled to full scale practice in flatwise, edgewise, and torsional degrees of freedom. The blade mass and stiffness parameters are such that the blade is aeroelastically similar to a full scale blade when operated at one-half full scale tip speeds and forward speeds. This permits the simulation of forward speeds substantially beyond the capabilities of the wind tunnel. The blades are fully articulated, with hydraulic lag dampers. The rotor is powered by an internal electric motor and transmission system and has a remotely controlled swashplate system for controlling collective and cyclic blade pitch. Rotor stresses are measured by strain gage bridges on the blades at various locations. The model incorporates three internal six-component strain gage balances to measure forces and moments separately on rotor, fuselage, and wing.

Three different size wings have been tested on the model, each in three different vertical locations, to determine rotor-wing-fuselage interference effects on performance, blade stresses, wing load distributions and tail downwash angles. Powered nacelles with dynamically scaled propellers have also been tested in various locations to determine rotor-propeller interference. Results of these investigations, which include simulated flight speeds up to 300 knots, are reported in Reference 5. While a number of measureable interference effects were found to exist, none would seriously compromise the compound helicopter concept if properly considered in the aircraft design stage.

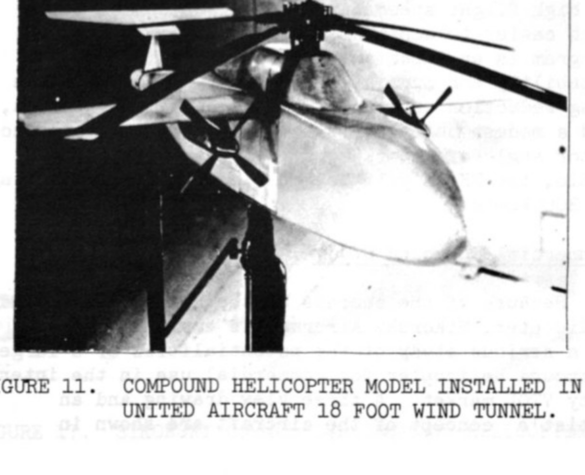
FIGURE 11. COMPOUND HELICOPTER MODEL INSTALLED IN UNITED AIRCRAFT 18 FOOT WIND TUNNEL.

More recently, the same model was utilized to investigate various forms of rotor instability at high speeds to provide data for correlation with theory and to provide an experimental confirmation of the location of stability boundaries. The forms of instability included in the study were flapping instability, retreating blade torsional divergence, flap-lag instability, stall flutter, and classical flutter. Simulated speeds up to 330 knots and advance ratios up to 1.8 were attained in these tests. Variables in the program, in addition to rotor operating conditions, were blade chordwise center of gravity location and pitch-flap coupling. This research program, supported by U. S. Army AVLABS, has indicated that rotor stability limits can be readily avoided to flight speeds beyond 300 knots.

Operation at high advance ratio has also been verified in a full scale wind tunnel test of a standard Sikorsky articulated rotor system. A full scale CH-34 (Sikorsky S-58) rotor was tested in the NASA Ames 40 by 80 foot wind tunnel (Figure 12) in two series of tests during which data on performance and vibratory loads were obtained at rotor advance ratios as high as 1.05 at the maximum available tunnel speed of 197 knots. No basic rotor limitation was encountered, and higher forward speeds could have been reached if the tunnel capacity permitted. These tests, supported by U. S. Army AVLABS, are reported in Reference 6.

The most significant research on the compound helicopter has been that conducted in flight. With support from the U. S. Naval Air Systems Command and U. S. Army AVLABS, Sikorsky Aircraft has conducted numerous flight investigations on the NH-3A high speed research helicopter (company designation S-61F). This aircraft is shown in two of its configurations in Figures 13 and 14. It is an extensively modified U. S. Navy SH-3A helicopter, with a gross weight of approximately 19,000 pounds. The design incorporates the addition of two J-60 P2 turbojets having a static thrust rating of 2,900 pounds each. A wing was incorporated with a span of 32 feet, an area of 170 square feet, and full span simple flaps capable of up or down deflection. The horizontal and vertical tail surfaces were greatly enlarged from the basic SH-3A for improved stability at high speeds, and elevator and rudder were

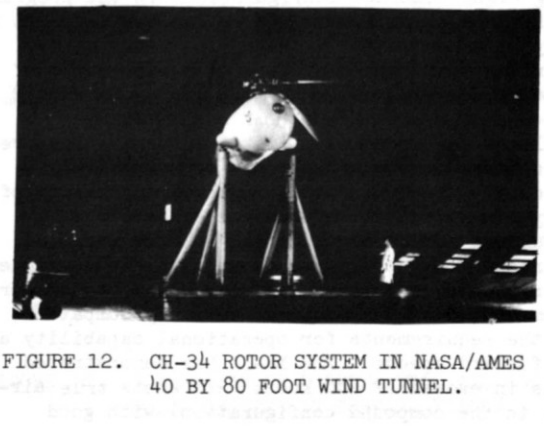
FIGURE 12. CH-34 ROTOR SYSTEM IN NASA/AMES 40 BY 80 FOOT WIND TUNNEL.

FIGURE 13. NH-3A RESEARCH HELICOPTER WITH JET THRUST AUGMENTATION

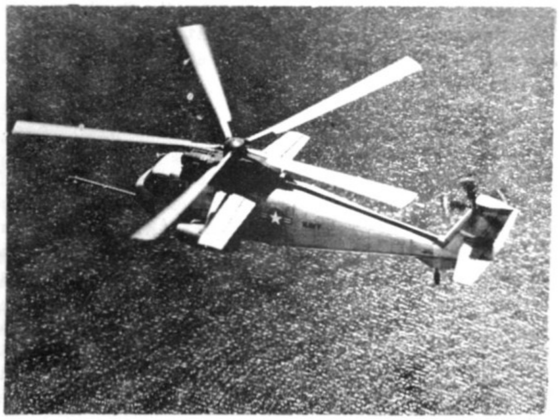

FIGURE 14. NH-3A RESEARCH HELICOPTER - COMPOUND CONFIGURATION

incorporated for trim control by means of separate actuators. The aircraft has been flown with and without the auxiliary turbojets and with and without the wing. It has also been flown with five-bladed and six-bladed rotor systems and with blades incorporating 4 degrees of twist in addition to the standard 8 degree twist blades.

The major objectives of the initial series of flight programs are listed in Figure 15. The first major item, to demonstrate improved aircraft capability, was aimed at eliminating the limitations and deficiencies of the pure helicopter at high speeds. The second major item, that of studying the influence of a number of independent design parameters on aircraft configurations, was satisfied by flying eight distinct configurations in the program. The third major objective was to use the aircraft as a "flying wind tunnel" to determine rotor system performance and capabilities over a wide range of operating conditions.

NH 3A RESEARCH HELICOPTER PROGRAM

MAJOR OBJECTIVES

DEMONSTRATE IMPROVED AIRCRAFT CAPABILITY

SPEEDS TO AT LEAST 200 KNOTS
GOOD USEFUL LOAD

with	LOW VIBRATION	IMPROVED FLYING QUALITIES
	LOW STRESSES	GOOD MANEUVERABILITY

DETERMINE INFLUENCE OF CONFIGURATION DESIGN PARAMETERS ON CHARACTERISTICS

variables:	NUMBER OF BLADES	
	BLADE TWIST	WINGS
	AUXILIARY PROPULSION	LONGITUDINAL TRIM

EXPERIMENTAL DETERMINATION OF ROTOR CAPABILITIES AT HIGH SPEED

LIFT AND PROPULSION FORCE ENVELOPES
POWER HANDLING CAPABILITY
CONTROL POWER, FLAPPING CHARACTERISTICS, DYNAMIC BEHAVIOR
ROTOR-WING INTERFERENCE

FIGURE 15. MAJOR OBJECTIVES OF FLIGHT PROGRAM

All of the objectives listed in Figure 15 have been achieved. The program has been extremely successful in demonstrating improved capability of rotary wing aircraft through the technique of compounding and in accumulating a large store of research data to permit the design of future higher performance aircraft. The fully articulated rotor system was demonstrated to be entirely compatible with the requirements for operational capability at high forward speeds. The NH-3A has demonstrated speeds in excess of 200 knots (221 knots true airspeed in the compound configuration) with good useful loads, low vibration levels, low stresses, good flying qualities, and a high load factor capability (2.25 g's at 160 knots). The only deterrent to higher speeds was the limitation of installed thrust. Other more specific conclusions include the following: (a) blade stresses at high speed were acceptable and were reduced by rotor unloading and by reduced blade twist, (b) vibration levels at high speed were acceptable and were markedly reduced with the six-bladed rotor, (c) the large horizontal stabilizer greatly improved longitudinal stability, and good inherent high-speed flying qualities were achieved without any type of artificial stabilization, (d) tail rotor stresses at high speeds were acceptable and could be significantly reduced by providing anti-torque forces with the vertical tail.

More detailed information on the flight research program on the NH-3A helicopter is available in References 7 and 8. At the time of writing this paper, the aircraft is engaged in a controls integration research program, under sponsorship of the U. S. Naval Air Systems Command. Previously the pilot's flight controls were connected to the rotor blade pitch controls only. In the present program the elevator and rudder have been connected with the longitudinal cyclic pitch stick and rudder pedals, respectively. The wing flaps have been converted to "flaperons", having both flap and aileron type motion, with the aileron function connected to the lateral cyclic stick. Thus airplane type controls have been combined with conventional helicopter controls about all three axes. The pilots report that handling qualities of the aircraft are distinctly improved at high flight speeds, with precise control being much easier to achieve. This control integration program is an important step in achieving a capability for much higher forward speeds. With a drag reduction program, increased auxiliary thrust, and a modest degree of pitch-flap coupling to reduce rotor angle of attack sensitivity at high advance ratio, the NH-3A will be capable of flight speeds up to 300 knots.

Commercial Compound Study

Because of the success of the research compound helicopter, Sikorsky Aircraft is currently engaged in a serious study of the potentialities of a large compound helicopter for commercial use in the intercity VTOL market. A three view drawing and an artist's concept of the aircraft are shown in

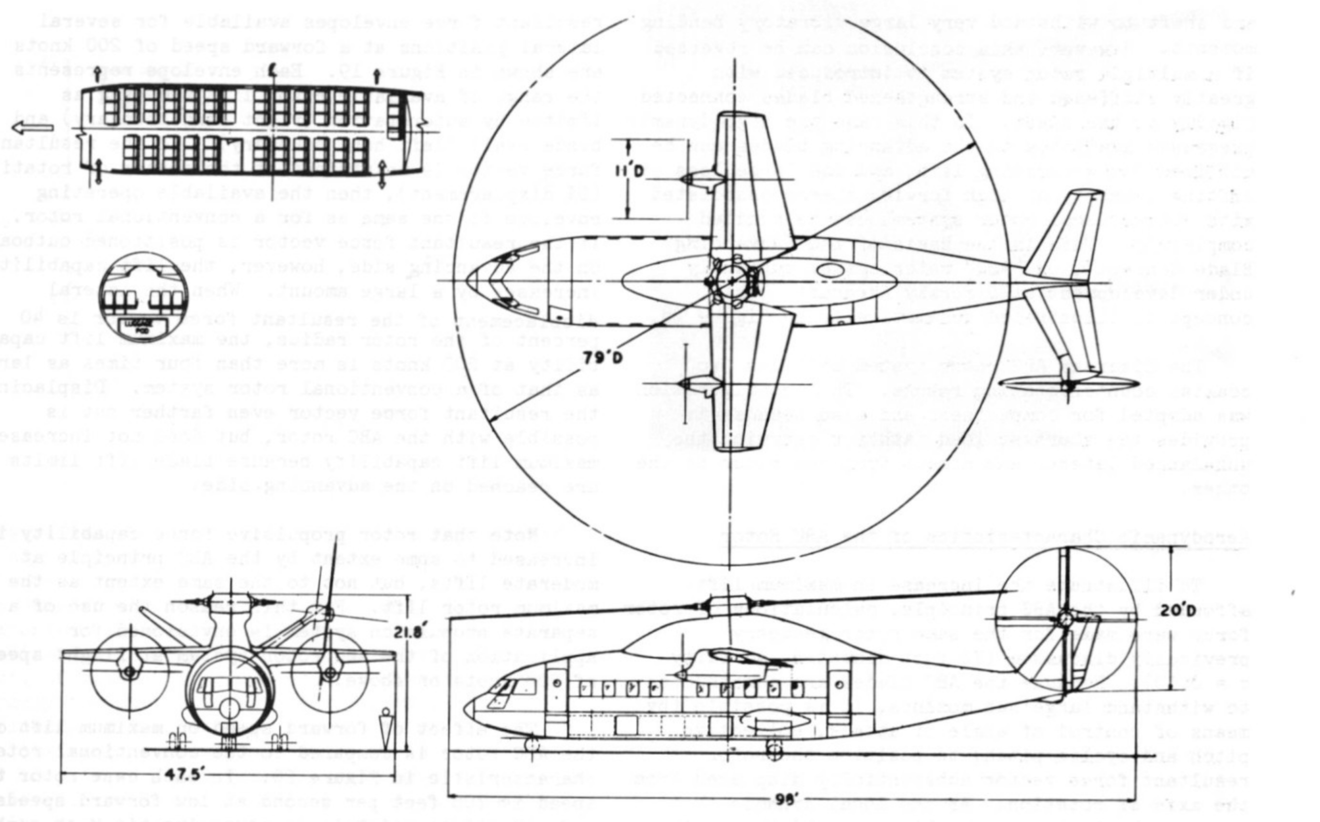

FIGURE 16. SIKORSKY COMMERCIAL COMPOUND HELICOPTER DESIGN

Figures 16 and 17. The aircraft would be based to some extent on the dynamic components of existing designs, such as the CH-53 (S-65) transport helicopter and the S-64B growth version of the Sikorsky Flying Crane. The commercial compound would have a passenger capacity of approximately 75 and a gross weight of approximately 60,000 pounds. Design cruise speed is 230 knots at an altitude of 8,000 feet, with a range of 200 nautical miles plus reserves. Three engines provide excellent flight safety in case of an engine failure at any point.

Projected direct operating costs for this commercial compound helicopter approach 3 cents per available seat mile, making possible a profitable short haul VTOL transportation system that can open up the inter-city VTOL market. The present tentative development schedule calls for first flight of a prototype aircraft in 1971, and, following FAA certification for category A Instrument Flight Regulations,commercial availability by 1973.

FIGURE 17. SIKORSKY COMMERCIAL COMPOUND HELICOPTER

ADVANCING BLADE CONCEPT

As discussed in the previous section entitled "Rotor Performance Limitations", it was stated that conventional rotor systems are not able to utilize the large dynamic pressures that exist on the advancing half of the rotor disk in forward flight. The reason for this is (a) for single rotor helicopters, the rotor rolling moment must be essentially zero due to lateral trim requirements, and, (b) even if this requirement is negated through the use of multiple lifting rotors, no conventional rotor system is able to support large rolling moments, either because of flapping hinges or limited capacity of the blade structure, rotor head,

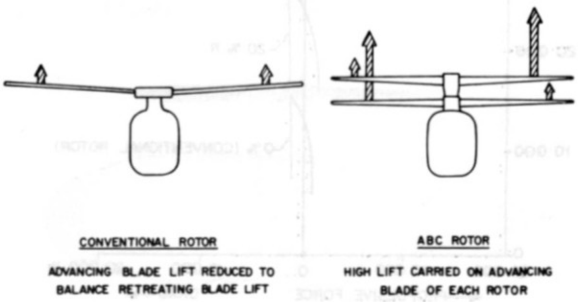

FIGURE 18. COMPARISON OF CONVENTIONAL AND ABC ROTOR SYSTEMS IN FORWARD FLIGHT

and shaft to withstand very large vibratory bending moments. However, this conclusion can be reversed if a multiple rotor system is introduced with greatly stiffened and strengthened blades connected rigidly to the shaft. In this case the high dynamic pressures available to the advancing blades can be utilized for generating lift, and the large loss of lifting capacity at high forward speeds associated with conventional rotor systems can be avoided completely. This is the basis of the "Advancing Blade Concept", or "ABC" rotor system currently under development at Sikorsky Aircraft. This concept is illustrated schematically in Figure 18.

The Sikorsky ABC rotor system utilizes two coaxial counterrotating rotors. This configuration was adopted for compactness and also because it provides the shortest load path for carrying the unbalanced lateral hub moment from one rotor to the other.

Aerodynamic Characteristics of the ABC Rotor

To illustrate the increase in maximum lift afforded by the ABC principle, calculations of rotor force were made for the same rotor geometry previously discussed (72 foot diameter, solidity $\sigma = 0.10$). Because the ABC blades are constructed to withstand large hub moments, it is possible (by means of control of angle of attack, collective pitch and cyclic pitch) to position the rotor resultant force vector substantially displaced from the axis of rotation. As the local dynamic pressures relative to the blade are higher on the advancing side of the disk in forward flight, it is logical to displace the rotor resultant force laterally toward the advancing tip. The rotor resultant force envelopes available for several lateral positions at a forward speed of 200 knots are shown in Figure 19. Each envelope represents the range of available rotor lift and drag as limited by autorotation (right hand boundary) and blade stall (left hand boundary). If the resultant force vector is maintained at the center of rotation (0% displacement), then the available operating envelope is the same as for a conventional rotor. If the resultant force vector is positioned outboard on the advancing side, however, the lift capability increases by a large amount. When the lateral displacement of the resultant force vector is 40 percent of the rotor radius, the maximum lift capability at 200 knots is more than four times as large as that of a conventional rotor system. Displacing the resultant force vector even farther out is possible with the ABC rotor, but does not increase maximum lift capability because blade lift limits are reached on the advancing side.

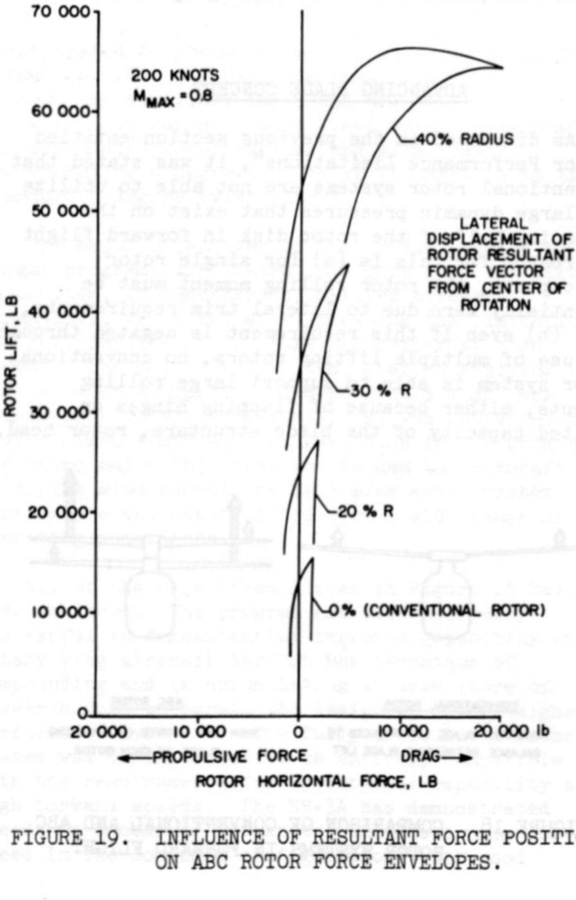

FIGURE 19. INFLUENCE OF RESULTANT FORCE POSITION ON ABC ROTOR FORCE ENVELOPES.

Note that rotor propulsive force capability is increased to some extent by the ABC principle at moderate lifts, but not to the same extent as the maximum rotor lift. For this reason the use of a separate propulsion system is envisioned for application of the ABC rotor system at flight speeds of 200 knots or above.

The effect of forward speed on maximum lift on the ABC rotor is compared to the conventional rotor characteristic in Figure 20. In each case rotor tip speed is 700 feet per second at low forward speeds, and reduced to maintain an advancing tip Mach number of 0.8 at high forward speeds. Unlike the conventional rotor, the lift capability of the ABC system increases with forward speed and remains above the maximum hovering lift value. At higher advancing tip Mach numbers, the ABC lift capability is further increased. Thus the altitude and maneuvering capability of a helicopter with an ABC rotor increases with forward speed, without the necessity of a wing which is required for high speeds with a conventional rotor system.

The lift-drag ratio of the ABC rotor at moderate lifts is also greater than that available from a conventional rotor system. The L/D of the assumed rotor at a lift of 40,000 pounds is presented in Figure 21 as a function of the lateral displacement of the resultant force vector at three forward speeds. As may be seen, at each forward speed there is an optimum force vector displacement for achievement of maximum L/D. This optimum displacement increases with speed. It should be noted that rotor L/D values, not including rotor head drag, increase with increasing

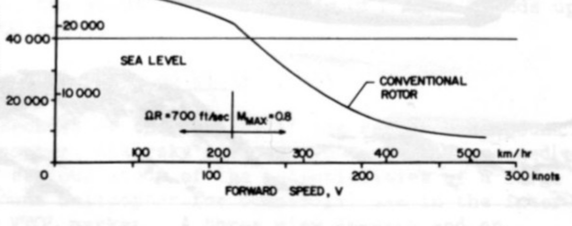

FIGURE 20. EFFECT OF FORWARD SPEED ON ROTOR LIFT CAPABILITY.

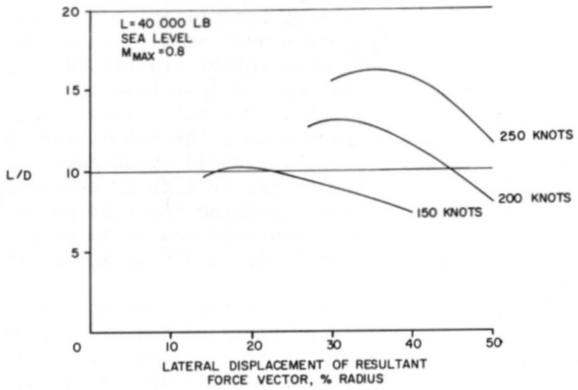

FIGURE 21. ABC ROTOR LIFT-DRAG RATIOS.

forward speeds, reaching a value of approximately 16 at 250 knots. This is more than double the L/D available from a conventional rotor alone at the same speed and Mach number condition, and comparable to the lift-drag ratio of a wing-rotor combination (Figure 8). Rotor head and pylon drag must, of course, be considered as discussed previously for conventional rotor systems. The influence of this drag on overall rotor L/D will be qualitatively similar to that shown in Figures 9 and 10. If very low parasite drag penalties can be achieved, the ABC rotor system offers the possibility of efficient cruise at forward speeds well above 300 knots.

ABC Rotor Development

Sikorsky Aircraft has verified the high lifting potential of the ABC rotor in a number of small scale tests. Because of its desirable performance characteristics as well as advantages it affords in aircraft design, Sikorsky has proceeded with the development of a full scale rotor system. This rotor, scheduled to be tested in the NASA Ames 40 by 80 foot wind tunnel, is 40 feet in diameter. A drawing of the rotor system on the wind tunnel test module is shown in Figure 22. The test module houses the electric drive motors, reduction gear box, and tne rotor swashplate control systems. Blade pitch control horns and pushrods are external to the shaft for the lower rotor, and internal for the upper rotor. The lower rotor blades are not preconed, but the upper rotor blades have a precone angle of 5 degrees, to provide additional tip

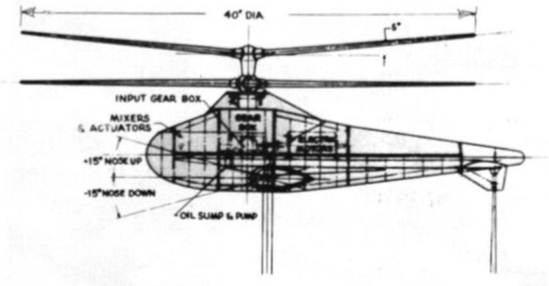

FIGURE 22. ABC ROTOR ON TEST MODULE FOR NASA AMES 40 BY 80 FOOT WIND TUNNEL.

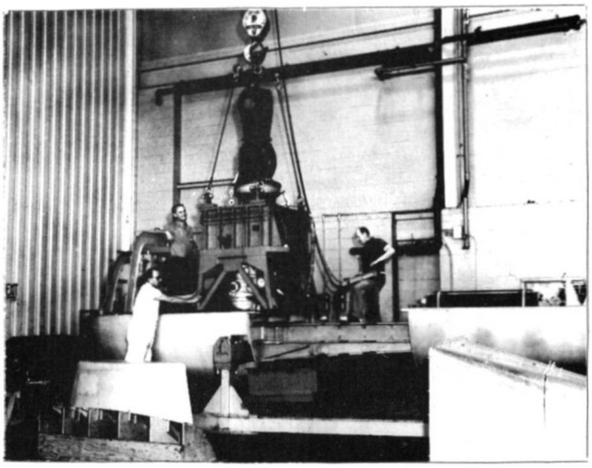

FIGURE 23. ROTOR HUB AND TRANSMISSION ON TEST MODULE.

clearance and to minimize the length of the shaft between rotor hubs. Each rotor has three blades. A photograph of the full scale rotor hub and transmission mounted on the test module is shown in Figure 23.

Development of the blades for the ABC rotor system has required the use of modern materials and fabrication technology. Because each blade experiences a large variation in lift during each revolution in forward flight and a correspondingly large vibratory bending moment, the blades must be much stronger and less flexible than conventional blades. The blades of the Sikorsky ABC rotor are, in fact, several times stiffer than blades of other rotor systems that have been labeled "rigid", but which are in reality quite flexible even though hingeless. It was found that conventional materials such as aluminum and steel are not capable of providing a satisfactory structure for the ABC blades with reasonable limits of airfoil thickness ratios and blade weights. However, newer materials such as titanium and high strength fiber composites do satisfy the structural requirements and make the concept achievable.

The blades for the 40 foot test rotor are based on the use of a single piece titanium spar. This spar will be a tapered, twisted, hollow tube of varying wall thickness. Blade cross sections at the root and tip are shown in Figure 24. The airfoil varies from a 28 percent thick section with a 22 inch chord at the root to a 6 percent thick 11 inch chord section at the tip. Aluminum honeycomb is used as a core for the trailing edge and plastic foam provides the nose shape. The entire section is covered with a skin of fiberglass-plastic.

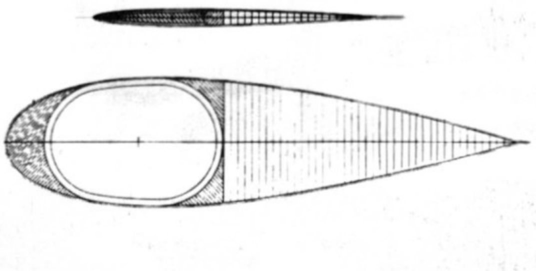

FIGURE 24. ABC BLADE CROSS SECTIONS AT ROOT AND TIP.

FIGURE 25. ABC FLIGHT DEMONSTRATION AIRCRAFT

The rotor system weight is minimized by designing to somewhat higher disk loadings than in conventional practice. No loss of useful hovering lift per unit power is anticipated, however, because of compensating aerodynamic advantages of the ABC system. These include a higher rotor hover figure of merit due to elimination of slipstream rotation, elimination of the need of an anti-torque tail rotor, and elimination of the vertical drag penalty of a wing. Advanced fiber composite materials with high stiffness to weight ratios should allow the use of more conventional disk loadings.

The full scale wind tunnel tests will provide performance data, information on control power and stability derivatives, and should substantiate the rotor structural design. It is planned that the 40 foot test rotor will be used subsequently in a full scale flight demonstration aircraft. This aircraft, an illustration of which is shown in Figure 25, will have a gross weight of approximately 16,500 pounds. With 3,800 shaft horsepower installed and a 10 foot diameter pusher propeller, maximum speed potential of the demonstration aircraft is on the order of 240 knots.

TILT ROTOR AND STOWED ROTOR CONCEPTS

Achievement of the maximum speed potential of rotary wing aircraft in a competitively economic fashion requires that the parasite drag penalty of the rotor system at high speeds be greatly reduced or eliminated. One means of accomplishing this is the tilt rotor configuration such as that shown in Figure 26. The side-by-side rotors are tilted forward 90 degrees to become low disk loading propellers in cruise flight. The rotor head drag, which is difficult to reduce when the rotor disk is horizontal, is quite readily reduced by an axisymmetric fairing in the propeller mode of operation. Sikorsky Aircraft has been studying the tilt rotor configuration extensively and believes it to be a promising concept for speeds up to 350 to 400 knots.

All aircraft types have inherent problems and limitations. One of the problems of the tilt rotor is excessive blade area in the propeller mode, making it difficult to achieve high propulsive efficiency in cruise. The total blade area is determined by hover and low speed requirements, for which the rotor must support the entire aircraft gross weight. Assuming a reasonably high overall lift-drag ratio in cruise, the drag to be overcome is only a small fraction of the gross weight, so that the rotor thrust capability as a propeller is excessive. Reasonably good propeller efficiencies may be achieved by use of high twist blades combined with tip speed reductions of 40 or 50 percent of the hover value, although this requires some degree of compromise and complexity in the power transmission system. Other problems of the tilt rotor aircraft are mechanical stability limits, such as propeller whirl mode flutter, and gust sensitivity and other flying qualities problems at high speed.

The tilt rotor configuration can be converted into a stowed rotor aircraft by providing cruise fans or other separate propulsion means and a system for feathering and stowing the rotor blades along wing tip pods. Sikorsky Aircraft has labeled this configuration the "Trivertiplane" because three distinct flight modes are possible: low speed helicopter mode with rotors in the upright position, propeller mode for intermediate speeds, and stowed rotor mode for high speed. It should be noted that the stowed rotor mode eliminates many of the problems of the basic tilt rotor at high forward speeds and extends maximum speed capability to approximately 500 knots, with relatively low values of empty to gross weight ratio. A picture of the Trivertiplane configuration is shown in Figure 27.

For the highest speed potential, high subsonic or even supersonic, the stowed rotor based on the single rotor configuration appears to be optimum.

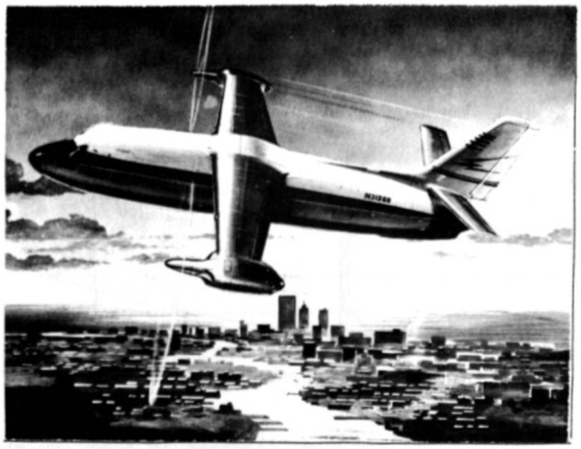

FIGURE 26. TILT ROTOR VTOL

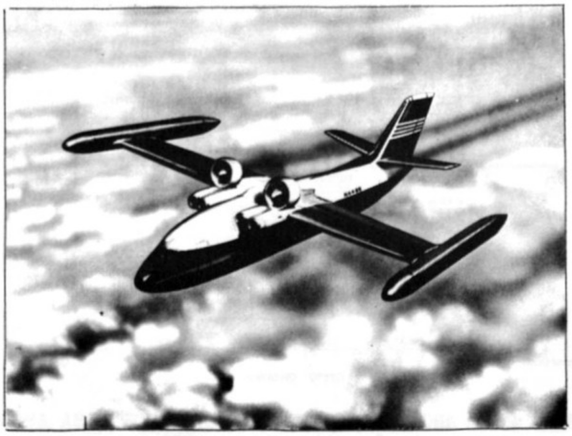

FIGURE 27. SIKORSKY TRIVERTIPLANE TILT-STOWED ROTOR

Unlike the tilt-rotor configurations, the wing is independent of the rotors and can be very thin and/or swept back as required above speeds of 500 knots. In principle the rotor can be retracted completely so that no parasite drag penalty remains in high speed flight, although generally in practice the stowage volume required will have some residual drag, just as any other form of high speed VTOL will have some excess volume required for the low speed lift system.

Sikorsky Aircraft has been studying various stowed rotor concepts for many years, concentrating initially on one and two-bladed gas drive rotor systems. Some of these studies are reported in Reference 9. More recently the studies have concentrated on shaft driven, multi-bladed main rotor configurations. The optimum number of blades for a wide variety of applications has been determined to be four. At least three blades are desirable for reason of achieving low vibration levels in helicopter flight, but three blades produce unacceptably large pitching and rolling moments during conversion in a turbulent atmosphere. This results from aerodynamic sweepback effects which cause large variations in the lift curve slope of each individual blade under slowly rotating conditions during rotor stops or starts. With four blades this effect is largely cancelled by rotor symmetry, because each blade has at all times another blade of the same instantaneous sweep value to balance it on the opposite side of the center of gravity. More than four blades are undesirable because blade aspect ratios become too high and the aeroelastic problems in conversion become excessive.

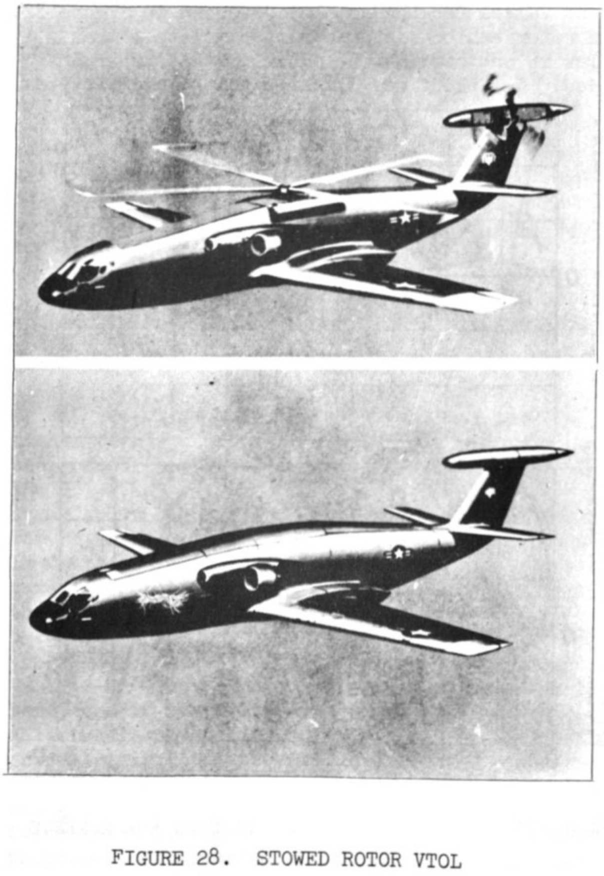

FIGURE 28. STOWED ROTOR VTOL

The stowed rotor configuration resulting from a recent design study is shown in Figure 28. In the helicopter mode shaft power is obtained from power turbines driven by the basic gas generator engines. In the high speed rotor-stowed mode the gas generator exhaust is diverted to drive cruise fans. Conversion speed is approximately 120 knots in this design.

Development of a successful stowed rotor requires the solution of several significant problems, most of which are associated with the conversion from one flight mode to the other. These problems include aeroelastic deformations and instabilities, and difficulties in achieving adequate stability and control. Solutions by conventional means are possible but will not be easy. A means of avoiding most of these problems is discussed in the next section.

TELESCOPING ROTOR SYSTEM

One of the new and promising approaches to the achievement of a high performance, low disk loading VTOL aircraft envisions the use of a rotor system which is capable of changing diameter in flight. This rotor system, which Sikorsky Aircraft has labeled "TRAC", was aimed initially at stowed rotor configurations, but it has also been found to provide benefits to other types including the compound helicopter and the tilt rotor.

The problems of stopping and stowing a rotor in flight are severe. Conventional rotor blades are stiff when rotating but flexible when stopped. They are not appropriate for a stowed rotor because very large bending stresses and deformations would result and aeroelastic instabilities of various kinds would occur. Building the blades stronger and stiffer reduces these problems, but for rotors of practical weight the aeroelastic effects are still highly significant. Another problem is that high aerodynamic loads on the outer portions of the blades cause pitching and rolling moments which tend to upset the aircraft in conversion. Even with four blades these moments are large, so that achievement of satisfactory stability and control is a major aircraft design consideration.

These problems are reduced slightly by increasing disk loading, because blade length is reduced, but unless disk loading is increased way beyond normal helicopter values, the problems remain severe. The problems are also minimized by keeping conversion speeds low, but at the expense of requiring a wing that is oversize and overweight for high speed cruise.

The TRAC rotor system was designed to overcome these problems. Telescoping blades are utilized to reduce blade length to manageable values prior to rotor stopping so that aeroelastic problems and hub moments are greatly reduced. Blade stowage volume is also substantially decreased.

A schematic drawing of the TRAC blade is shown in Figure 29. The main lifting part of the blade extends along the outer half of the radius, where 90 percent of the lift is normally generated in hover. Inboard is a streamlined elliptical torque tube which generates some lift and which transmits the pitching motions from the control horn to the

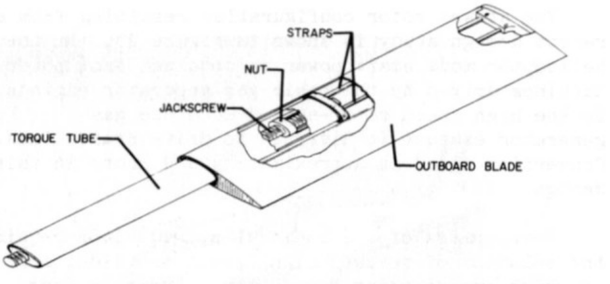

FIGURE 29. SIKORSKY TRAC TELESCOPING ROTOR BLADE-SCHEMATIC ARRANGEMENT.

outboard blade. During retraction the outboard blade slides along and encloses the torque tube. Inside the blade is a jackscrew and nut, which provide the linear motion during the retraction cycle, and a pair of straps connecting the nut to the blade tip. Minimum rotor diameter is on the order of 60 percent of maximum diameter. The basic concept is really quite simple, although a great deal of analysis has been required to establish the details of a workable design.

A schematic drawing of the rotor head and transmission is shown in Figure 30. Inside the rotor head is a simple differential gear set which is the heart of the mechanism. Both upper and lower bevel gears of this set are connected by coaxial shafts to a clutch or brake at the bottom of the transmission. Stopping the lower bevel gear with respect to the fuselage forces the pinions of the gear set to roll around the bevel gear and thus turn the jackscrew and retract the blades. Braking the upper bevel gear reverses the motion and extends the blades. This mechanism is simple and reliable. The differential gears are always fully engaged and the blades are completely synchronized. No separate power supply is required as the system is driven in both directions by the main shaft.

A thorough design study of this system has led to the conclusion that it is entirely feasible and mechanically sound. The weight of the system, while heavier than an aerodynamically equivalent rotor not designed for in-flight stopping, is comparable to weights of production rotor systems designed for aircraft carrier operation where automatic blade folding on the deck is required. The calculated weights were based on the use of current technology materials including aluminum, steel, and titanium.

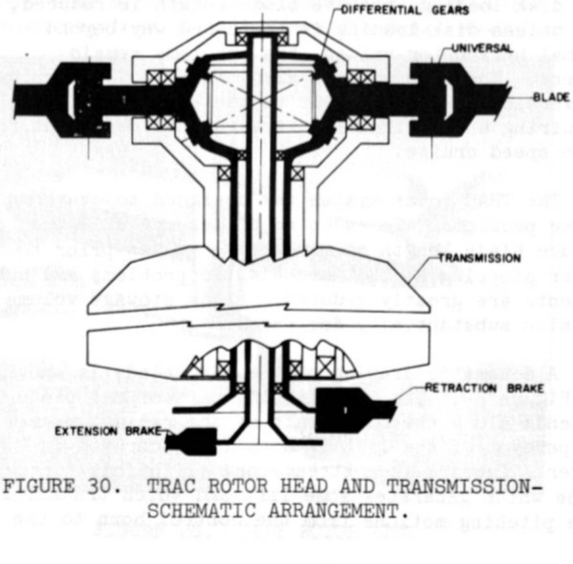

FIGURE 30. TRAC ROTOR HEAD AND TRANSMISSION-SCHEMATIC ARRANGEMENT.

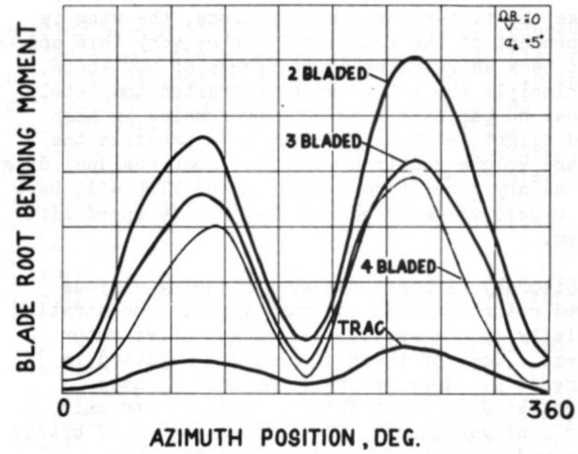

FIGURE 31. EFFECT OF CONFIGURATION ON BLADE ROOT BENDING IN CONVERSION

The benefits of the telescoping rotor were demonstrated in a wind tunnel test of a series of model rotors under conversion flight conditions. The series included 2, 3, and 4-bladed rotor of the same diameter and total blade area, and a reduced diameter 4-bladed rotor simulating the TRAC system at minimum diameter. A typical comparison of experimental blade root bending moments for one revolution for the four configurations is shown in Figure 31 for an angle of attack corresponding to a mild gust condition. As may be seen, the TRAC blade root moments are very much smaller than for any of the fixed diameter rotors.

The corresponding rotor pitching and rolling moment values for the models are shown in Figure 32. Each rotor exhibits a number of complete moment cycles in one revolution, equal to the number of blades. All the fixed diameter cases, and particu-

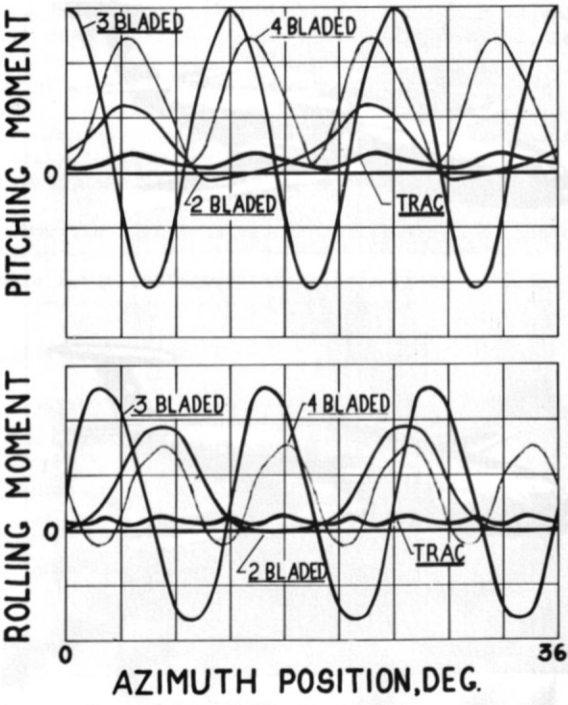

FIGURE 32. EFFECT OF CONFIGURATION ON HUB MOMENTS IN CONVERSION.

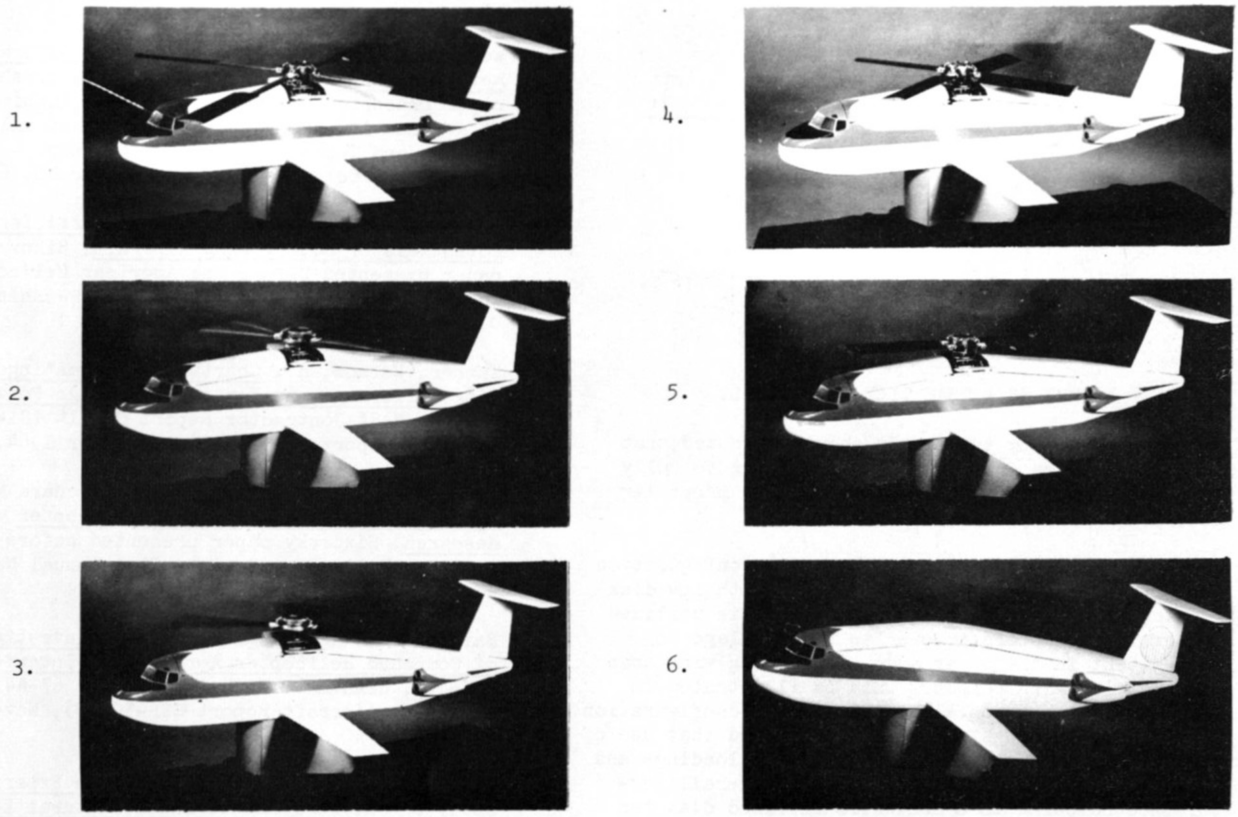

FIGURE 33. TRAC STOWED ROTOR CONVERSION SEQUENCE.

larly the three-bladed case, experienced hub moments that were higher than the control moments available from conventionally-sized elevator and ailerons. It is evident that the aircraft would be severely disturbed by gusts, so that some form of active gust alleviation system would be necessary. On the other hand, hub moments for the TRAC rotor were so much smaller that no severe problems of this nature are anticipated. This permits higher conversion speeds and use of a smaller and lighter wing designed for cruise.

Application of the TRAC rotor system to a single stowed rotor design is illustrated in Figure 33, which shows a sequence of operating conditions represented by a working demonstration model of somewhat arbitrary configuration. The first frame of the sequence shows the rotor stopped and the blades fully extended, a condition that may occur on the ground but not in flight. The next frame shows the rotor turning at maximum diameter, and the third frame shows the rotor contracted to minimum diameter. The rotor is then stopped and positioned as shown in frame 4. The blades are then repositioned parallel to the direction of flight and stowed in the upper part of the fuselage as shown in frames 5 and 6.

The TRAC rotor system also provides distinct benefits for the tilt rotor configuration. It alleviates the problem of excess blade area in the propeller mode and provides a desirable tip speed reduction without the complication of a large rpm change or a gear shift. The resulting benefits are illustrated in Figure 34 which shows calculated propeller efficiencies at 350 knots for a recent tilt rotor aircraft design study. The upper figure shows that for a given blade twist the retracted TRAC rotor provides substantially better propeller efficiency at any rpm than a fixed diameter rotor. The lower figure shows that for a given rpm, TRAC

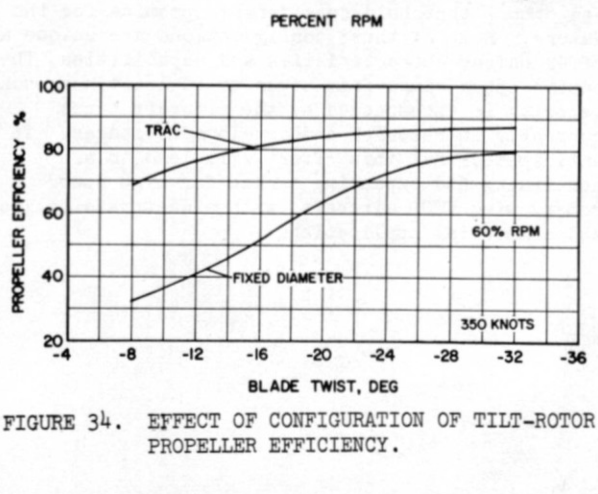

FIGURE 34. EFFECT OF CONFIGURATION OF TILT-ROTOR PROPELLER EFFICIENCY.

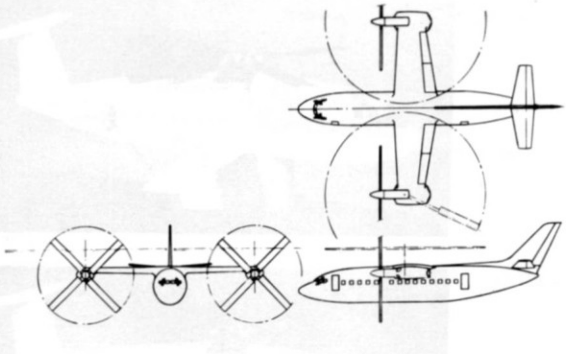

FIGURE 35. TRAC TILT ROTOR VTOL.

is superior at any twist. It should be noted that the twist values for the TRAC rotor refer to fully extended values; the actual twist in the propeller mode is only 60 percent of these values.

Another benefit for the tilt rotor configuration is that of providing a compact design with low disk loading. The variable diameter feature is utilized to permit the rotors to overlap the fuselage to some extent in the hover mode, minimizing wing span and reducing wing weight. This is illustrated in Figure 35 which shows a TRAC tilt rotor configuration. Comparative design studies have indicated that use of the telescoping rotor allows lower disk loadings and results in significant improvement in overall performance compared to a conventional fixed diameter tilt rotor.

Sikorsky Aircraft is currently fabricating a 9-foot diameter 4-bladed wind tunnel model of the TRAC rotor system, which will be dynamically similar to a full scale design previously established. This model will be tested in the near future under a U. S. Army AVLABS contract. It is being built in the single stowed rotor configuration, and will be tested at full scale tip speeds and forward speeds under a variety of conditions, including diameter changes and rotor starts and stops. The tests are aimed at determining performance, stresses, and general aeroelastic behavior.

CONCLUDING REMARKS

Sikorsky Aircraft is pursuing a broad spectrum of advanced rotary wing aircraft concepts, including one that has reached the production prototype stage and others that hold considerable promise for the future. Some of these configurations are unique and offer unique characteristics and capabilities. The entire speed range from hover to at least near-sonic velocity is encompassed by the aircraft types currently in research and development stages. It is anticipated that this effort will lead to a continuing and expanding market for high speed rotary wing VTOL aircraft, with wide-spread military and commercial applications.

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