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Conceptual Assessment of Two High-Speed Rotorcraft

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Recently completed high-speed rotorcraft design studies for NASA provide the basis to assess technology needs for the development of these aircraft. Preliminary analysis of several concepts possessing helicopter-like hover characteristics and cruise capabilities in the 450-kt regime, led to the selection of two concepts for further study. The concepts selected included the rotor/wing and the tilt wing. Designs, based on current technology for each, established a baseline configuration from which technology trade studies could be conducted. Technology anticipated to be ready for application in the year 2005 set the goals for the trade studies. An assessment of the technologies' impact on the effectiveness of the concept served as the basis to determine potential risk, payoff, and criticality. Advanced technology, applied to either of these concepts, significantly improves the effectiveness and the attributes of the concepts.

Nomenclature

c/D = ratio of wing chord to propeller diameter ratio
L/D = ratio of aircraft lift to drag
P/W = ratio of engine power to weight

Introduction

RENEWED interest in high-speed rotorcraft with relatively low disk loading influenced NASA to initiate a program to investigate and identify the enabling technologies required to develop this type of aircraft. Several of the armed services concurrently sponsored similar contracts, although from a more specialized perspective. In order to not restrict concept selection and creative thinking, NASA only specified the concepts to be of helicopter-like disk loading and capable of forward flight in the 450-kt range. The forward speed requirement represents a significant increase over existing V/STOL aircraft.

The study consisted of three tasks: 1) initial technology assessment and concept definition; 2) technology evaluation for selected concepts; and 3) the enabling technology plan. During the first task, a brainstorming session identified 16 concepts of varying viability. A qualitative evaluation of these concepts yielded five concepts, plus one variation, for further evaluation during the task. These concepts included the tilt rotor, tilt wing, rotor/wing, folding tilt rotor, and two variations of the trail rotor convertiplane. After sizing these concepts and comparing their attributes and vehicle effectiveness through trade studies, two concepts emerged as the most effective (Fig. 1). The results of the initial study indicated that concepts employing integrated lift/propulsion systems surpassed those using separate systems for helicopter and fixed wing modes.

The rotor/wing demonstrates capabilities and concept effectiveness greater than any other concept studied. This results from a cleaner cruise configuration and lower empty weight. Due to the amount of initial concept exploration in the mid-60s, including whirlstand, wind tunnel, dynamic model conversion, and transonic tests, much is known about this configuration. The XH-17 and XV-9A technology demonstrators incorporated reaction drive rotors in their designs. Since no new engine technology is required—such as convertible engine development—the risk and cost should be less than any of the folding concepts. However, desired engine development increases the utility and effectiveness of the concept. The rotor/wing appears as a moderate risk concept with a high payoff in effectiveness.

The tilt wing represents a proven concept. While essentially comparable to the tilt rotor in effectiveness, it possesses the potential for a lighter weight solution and eliminates the hover download characteristic of tilting rotor concepts. Eliminating the pitch fan using rotors instead of propellers may significantly improve handling qualities and agility in the low-speed regime. It offers a different concept from the rotor/wing and one which has not benefitted from advanced development, as has the tilt rotor.

Several missions were provided as options by NASA,[1] of which one was chosen for each concept. The selected mission for the tilt wing was a military transport (shown in Fig. 2), whereas the rotor/wing was assigned to a ground attack role (shown in Fig. 3).

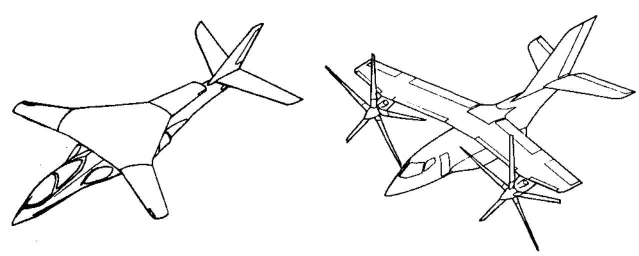

Fig. 1 Concepts selected from task 1 for further study.

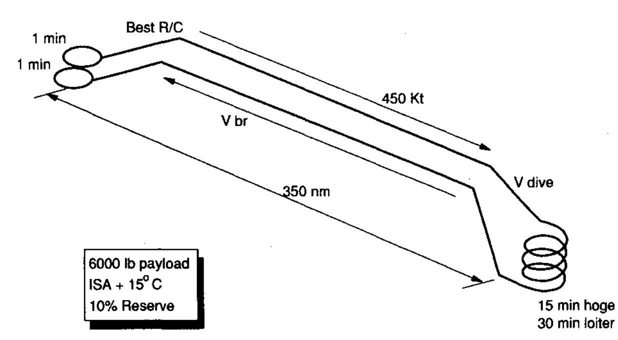

Fig. 2 Military transport mission (from Ref. 1).

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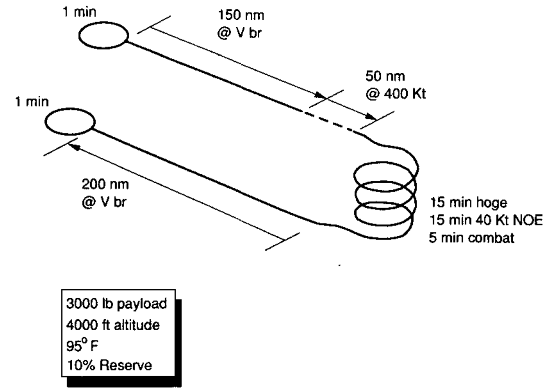

Fig. 3 Ground attack mission (from Ref. 1).

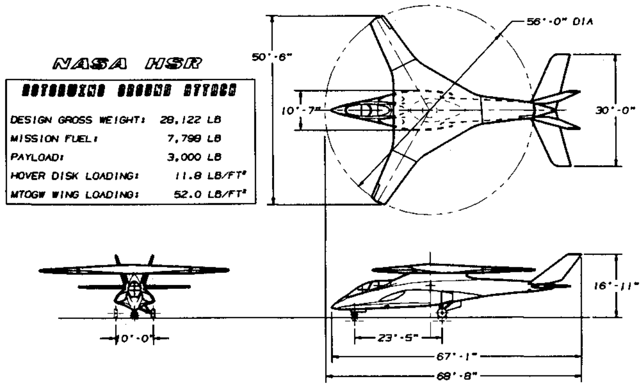

Fig. 4 Rotor/wing ground attack aircraft.

Rotor/Wing

General Description

The rotor/wing consists of a warm cycle, reaction-driven rotor, with a large triangular centerbody/hub and three short-span, wide-chord blades. For vertical and low-speed flight, the rotor is powered by ducting mixed flow turbofan engine exhaust gases through the hub and rotor blades out to tip jets. The rotor autorotates during conversion until the aircraft reaches conversion speed (about 170 kt), and the centerbody provides enough lift to achieve 1 *g* conversion. At this point, the rotor, off-loaded, stops to become a swept forward wing for cruise and high-speed flight. For simplicity, the use of airfoils with blunt leading and trailing edges and a feathering hinge eliminates the need for circulation control. The rotor/wing shown in Fig. 4 is configured for the ground attack role.

The forward fuselage accommodates a tandem crew station with duplicate controls for each. The forward fuel cell resides behind the aft crew station; the aft fuselage houses another fuel cell around the center of gravity (c.g.). The mission equipment package is located over the forward fuel cell. A 20-mm gun lies directly below the forward fuel cell, and the ammunition canister lies to the right of the gun. Two low bypass ratio turbofan engines are located on either side of the fuselage. The landing gear retract into the fuselage.

The rotor/wing attaches to the fuselage through a rigid mounting on a bearing which allows only rotational motion. The stub blades can only feather. The flexibility of the structure provides the necessary flapping motion for helicopter flight. A reaction drive system eliminates the heavy transmissions common to high-speed rotorcraft and provides a very simple system for both rotary- and fixed-wing operation. During conversion, diverter valves redirect engine exhaust gases aft for conventional forward thrust. A small thruster located in the tail boom provides yaw control in helicopter mode (no antitorque is required). Elevons provide pitch and roll control in fixed-wing flight.

Sizing

Sizing the rotor/wing depends on knowledge of the losses incurred while ducting the exhaust gases from the engine exit to the tip jet. Data from the Hughes XV-9A hot cycle helicopter were used to approximate these losses. Minor losses due to friction and heat loss significantly affect the efficiency of this type of power transmission.[2,3] However, elimination of the heavy transmission and antitorque device nearly compensates for the inefficiency.

Subdividing the blade duct into three sections allows for geometry variations and the losses for each section are computed from flow information at the beginning of each. XV-9A tip-nozzle efficiency is also assumed. The exit Mach number of the flow is constrained to below sonic conditions, and the mass flow then matches power available from the exit conditions to that required by the rotor. Since the internal duct size influences the chord size of the blade, for a specified t/c ratio, the sizing process is iterative.

Initial guesses at the gross weight, optimum disk loading, centerbody area, and rotor thickness determine rotor size and performance. The rotor thickness at the root is sized by the amount of mass flow needed at the tip, which is determined by the rotor power required. The blade thickness, rotor radius, and tip speed determine average blade lift coefficient. If the lift coefficient is too high (indicating rotor stall), new rotor geometry is needed to keep the rotor unstalled. Because rotor clearance of the vertical tail limits the rotor radius, root t/c controls the average blade lift coefficient. Limiting the maximum t/c to 20% produces an optimum rotor tip speed of 650 fps.

Figure 5 shows the sizing matrix with the appropriate constraints. Rotor radius and the ratio of centerbody radius to rotor radius ξ are the dependent parameters which drive the solution. The first represents disk loading, and the second, conversion wing loading. The conversion wing loading of 65 psf occurs at a conversion speed of 170 knots true air speed (KTAS) and a maximum pitch-up attitude of 15 deg. If ξ becomes too small, the centerbody wing loading exceeds that allowable for conversion. The value is not constant, because a larger rotor radius allows smaller values of ξ without exceeding the conversion wing loading limit. The maximum rotor radius represents a "soft" boundary, as it serves as the maximum allowable radius to avoid striking the vertical tail.

The final rotor/wing sizing produced an aircraft with sizing parameters shown in Table 1.

Conversion

The conversion of the rotor/wing requires careful consideration of two areas: 1) centerbody lift and 2) high advance ratios (rotor stop and start). Although the rotor/wing concept has never flown, extensive wind-tunnel tests have investigated conversion fully.

Data from the 1960s wind-tunnel tests, completed by Hughes Tool Company, determined the lift and drag characteristics

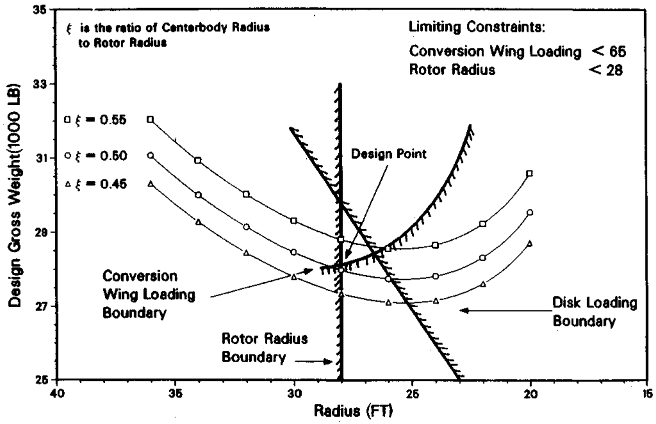

Fig. 5 Rotor/wing sizing carpet plot.

Table 1 Current technology rotor/wing design parameters

Gross weight	28,122 lb
Maximum sea level thrust	12,398 lb
Rotor figure of merit (P_{ind}/P_{tot})	0.844
Rotor radius	28.00 ft
Centerbody radius	14.25 ft
Disk loading	11.83
Wing loading	51.98
Aspect ratio	4.62
Hover tip speed	650 fps
Flat plate drag	12.34
Maximum L/D	10.92
Cruise TSFC	0.83

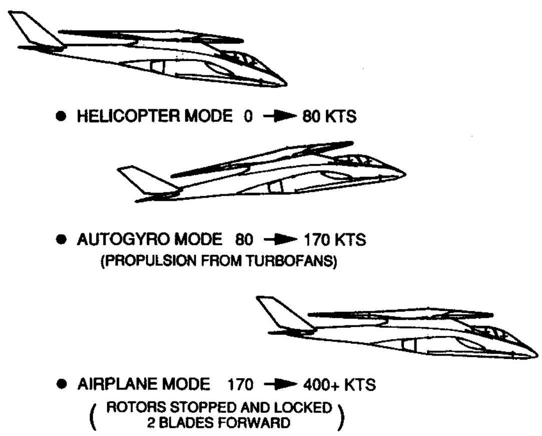

Fig. 6 Rotor/wing conversion process.

Table 2 Rotor/wing advanced technology goals

Technology	Rotor/wing
Materials and structure	Overall weight (−15% Primary structure) (−10% Secondary structure)
Propulsion	IHPTET Goals (−30.0% SFC, +120% T/W)
Drive train	N/A
Aerodynamics	Reduce cruise airfoil drag (−12.3% Drag coefficient) Increase conversion wing Loading (90 psf)
Flight controls	Reduce empennage size (−15% Area) Reduce weight (−10%)
Subsystems	Reduce weight (−10%)

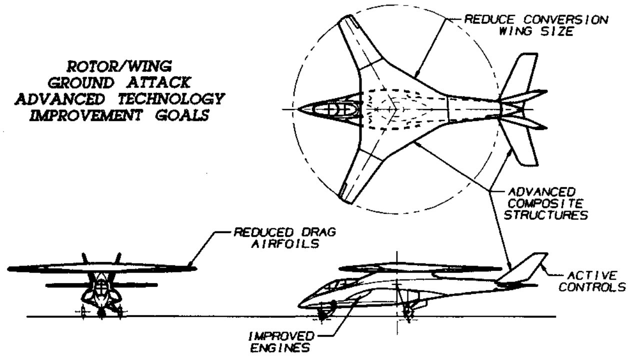

Fig. 7 Rotor/wing advanced technology application.

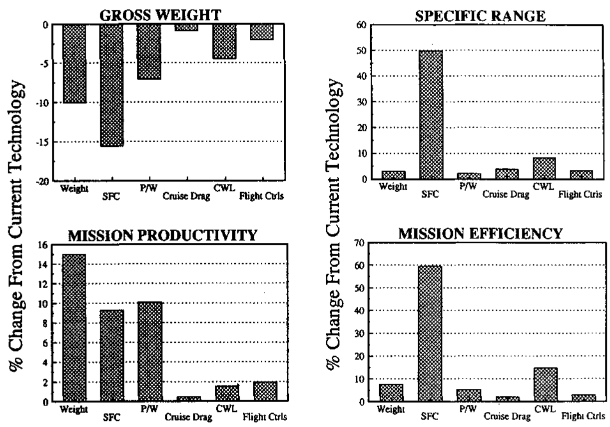

Fig. 8 Results of technology application to rotor/wing.

of various centerbody shapes. The test results show that a triangular centerbody can maintain a lift coefficient of 0.6 at 15 deg. With the centerbody rigidly attached to the fuselage, the fuselage attitude sets the centerbody angle of attack. Although the centerbody could operate at higher angles of attack, 15 deg represents the maximum practical aircraft attitude during conversion. This lift coefficient and the desired conversion speed of 170 kt, determine the centerbody size.

Analysis using CAMRAD JA[4] indicated that at moderate speeds in helicopter mode, rotor vibration could be a problem. Rotor hub loads tend to become excessive in helicopter mode above 100 kt. It also confirmed the sizing of the centerbody and rotor to be adequate to carry the rotor/wing from 80 to 120 kt in autogyro mode. Figure 6 shows the conversion process for the rotor/wing.

The greatest concern during conversion is stopping or starting the rotor in forward flight. As the advance ratio becomes very large, rotor vibrations increase. However, unloading the blades significantly reduces vibrations using cyclic pitch control. Additional oscillations occur due to the triangular centerbody. As the centerbody carries lift during conversion, the center of lift oscillates in an elliptical pattern with a frequency three times the rotor rotational speed, causing pitch and roll inputs during the last few revolutions. Reference 5 presents several suggestions to overcome this problem including cyclic pitch control, elevon deflection, and possibly the use of a four-bladed configuration.

Technology Trade Studies

Achievable technologies will determine the potential of the rotor/wing. A brainstorming session produced the technology matrix shown in Table 2. Application of all technologies indicates the size and shape of future rotor/wing aircraft. Figure 7 shows where the different technologies apply to the rotor/wing.

Since the missions of both the rotor/wing and the tilt wing have relatively long hover and/or nap of the earth (NOE) segments, conventional aircraft measures of effectiveness may be ineffective for technology impact assessment. Since the mission of each specifies a fixed payload, speed, and range, these parameters remain constant throughout the trade studies and the measures of effectiveness reduce to the following:

Gross weight

$$\text{Mission productivity} = W_{pay}/W_{emp}$$

$$\text{Mission efficiency} = W_{pay}/W_{fuel}$$

$$\text{Specific range} = V_{dash}/\dot{W}_{fuel}$$

The above relations show that mission productivity simply measures the empty weight needed to deliver a specified payload in a given mission. Likewise, mission efficiency is the fuel weight needed to deliver a specified payload for a given mission. The specific range listed above gives an indication of the vehicle's efficiency during the mission's high-speed dash segment.

These new measures of effectiveness are used to compare the vehicles with advanced technology to the baseline vehicles flying the same mission. Figure 8 shows the results of the individual application on the measures of effectiveness expressed as percent changes from the baseline values.

Gross Weight

The first graph in Fig. 8 shows the effect of the technologies outlined in Table 2 on rotor/wing gross weight. The integrated high performance turbine engine technology (IHPTET) phase III goals [30% specific fuel consumption (SFC) reduction and 120% increase in engine power-to-weight ratio] show the greatest impact on gross weight. The application of the IHPTET goals produces a savings in fuel and propulsion system weight, and also accounts for indirect savings in overall vehicle weight. The application of advanced structures and materials technology to the rotor/wing accounts for a 10% savings in gross weight. Unlike the application of the IHPTET goals, the advanced structures and materials application produce reductions in empty weight.

A decrease in the conversion wing loading decreases the wing area which corresponds to a decrease in wing weight and vehicle drag. Similarly, the decreased cruise drag and empennage size (through the application of active flight controls) reflect a reduction in vehicle drag. This reduction in drag does not have as large an impact on the gross weight as the other technology applications due to the short cruise segments and long hover and NOE segments of the ground attack mission.

Mission Productivity

The application of advanced structure and materials shows the greatest impact in mission productivity due to the direct impact of this technology on empty weight. The increase in power-to-weight ratio shows a significant impact on mission productivity as expected, however, the SFC reduction also shows a large impact. This is due mainly to the large reduction in the size of the fuel system. The effect of the SFC reduction also demonstrates the magnitude of cascading or indirect empty weight reduction due to a large reduction in gross weight. The reduction of the empennage size shows a greater effect on mission productivity than the reduction in conversion wing loading. This is due mainly to the increase in rotor aspect ratio and blade area which accompanies any reduction in centerbody area. The reduction in cruise drag effects mission productivity only slightly through an indirect reduction in empty weight.

Mission Efficiency

As expected, the mission efficiency graph in Fig. 8 shows that the phase III IHPTET SFC reduction has, by far, the greatest impact. Conversion wing loading shows a slightly higher impact on mission efficiency than the other technologies because it not only saves fuel in cruise, but increases the efficiency of the rotor in helicopter mode. The other areas of applied technology seem to indicate that for the ground attack mission, a reduction in weight and an increase in hover efficiency has more effect on the fuel required than cruise drag reduction.

Specific Range

The specific range graph of Fig. 8 roughly resembles the mission efficiency graph, showing that the phase III IHPTET SFC reduction has the greatest impact on specific range. However, there are some differences between the two graphs. Notice that the cruise drag and conversion wing loading reductions have a larger impact on specific range than the other measures of effectiveness. This is because specific range is a measure of the dash speed divided by the dash fuel flow. Thus, any reduction in drag will have a larger impact in specific range than technologies that impact empty weight.

Combined Results

Figure 9 shows the effect of applying all of the technologies simultaneously to the rotor/wing compared to the baseline vehicle. The impact of all of the technologies combined indicates a large potential improvement of rotor/wing measures of effectiveness in the ground attack mission. While the 29% reduction in gross weight is very significant, the realization of the phase III IHPTET goals will enable the rotor/wing to be a very efficient machine. Although these goals for SFC and engine power-to-weight ratio are ambitious, the benefits are extraordinary both through increased efficiency and higher bypass ratio.

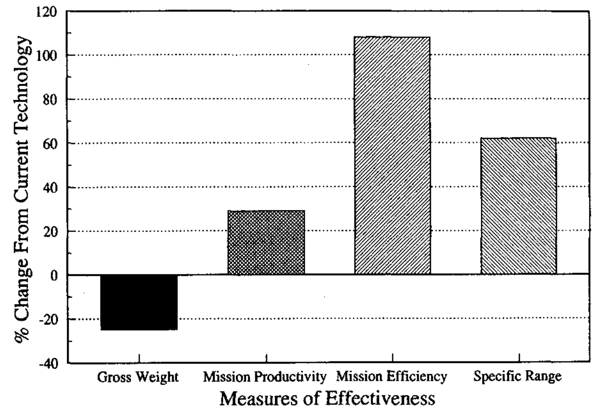

Fig. 9 Effect of combined technology application on rotor/wing effectiveness.

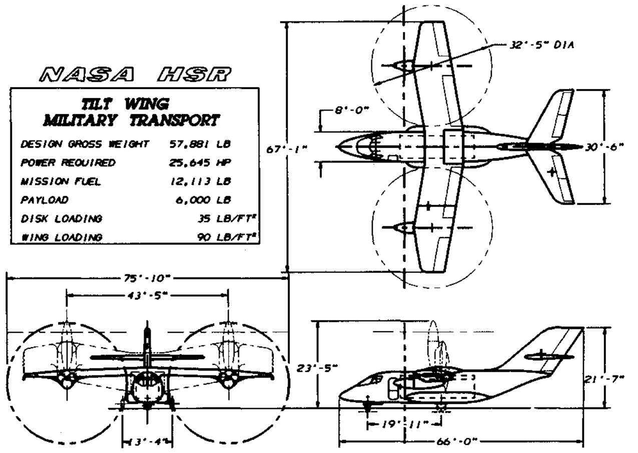

Fig. 10 Tilt wing military transport.

Tilt Wing

General Description

The tilt wing (shown in Fig. 10) is configured as a military transport. As in conventional tilt wings, the wing tilts upward to a vertical position for low-speed or vertical flight, and tilts to the horizontal position for fixed-wing flight. Rotors, rather than propellers with beta controls, provide propulsive thrust and eliminate the need for a pitch fan.

The fuselage for the current tilt wing contains a 6 × 6 × 20-ft cargo bay. The crew station consists of a two place, side-by-side arrangement with duplicate controls for both. The mission equipment package (MEP) resides behind the right crew station, forward of the cargo bay, stacked in a five tier arrangement for easy access. Sponsons on the lower fuselage house the main landing gear, whereas the nose landing gear is located beneath the crew stations. Fuel cells are fore and aft of the main landing gear in both sponsons. Additionally, two fuel cells are located in the wing.

The high-aspect ratio wing consists of 10 deg of forward sweep inboard of the rotor pylons, and 10-deg aft sweep outboard. The wing sweep allows clearance for rotor flapping and delays drag divergence in high-speed flight. The high mounted wing has 2 deg of anhedral for enhanced maneuverability. Trailing edge slotted flaperons extend from 70% chord to the trailing edge. The wing tilts about a conversion hinge located at 50% chord in the local area above the fuselage. Hinging at 50% chord reduces the inertia of the tilting wing (vs hinging further aft), subsequently reducing transmitted loads through the hinge and conversion actuators. Additionally, a minimum of 50% chord is considered necessary for the wing torque box carry-through structure. The local wing structure aft of the hinge and directly above the fuselage remains fixed during conversion. Two conversion actuators provide redundancy.

The rotor system consists of two five-bladed rotors, with the rotor pylon underslung below the wing. This offset maintains the c.g. below the center of lift in both flight modes. Additionally, the underslung pylon aids in preserving flow attachment on the wing for improved conversion characteristics. Two turboshaft engines power each rotor, with no cross shafting between the two rotor systems. Each engine provides all of the required power to its rotor, should the other engine become inoperative.

The empennage includes a single vertical stabilizer with a horizontal tail mounted conventionally. Each half of the horizontal tail has inboard and outboard elevators.

Sizing

VASCOMP II[6] provided the means to size the tilt wing. Airfoil data obtained through recent design and wind-tunnel tests represent state-of-the-art characteristics. Propulsive efficiencies were determined using predictive codes from the Douglas Aircraft Company. The result of the sizing exercise resulted in the graph shown in Fig. 11.

A tilt wing reconversion study provided a wing loading constraint for a given disk loading. Instead of using a fixed chord-to-diameter ratio, a matrix of points was investigated, varying several parameters. This study determined the conversion boundary on the sizing matrix. The constraint ensures reconversion with at least 8-deg descent angle at all airspeeds. Two additional boundaries appear in this figure. The first, a maximum rotor radius boundary, places the rotor hub at the wing tip with rotor-fuselage clearance of 1 ft. Increasing the wing area with the same disk loading results in a portion of the wing outside the rotor slipstream; an unacceptable configuration for a tilt wing. The second is based on the maximum disk loading boundary determined by Wernicke[7] to result in overturning moments in ground effect. Wernicke presents a relationship for the allowable disk loading for a twin rotor helicopter vs gross weight. This appears in Fig. 11 as a curve, but far to the right of the design point. For this reason, a disk loading limit of 40 psf was chosen based on previous twin rotor tilt wing designs. The tilt wing sizing process produces a four engine, two rotor aircraft with final sizing parameters shown in Table 3.

Initial assumptions envisioned the tilt wing with two rotors and two engines. A sensitivity study showed no weight advantages with four rotors; but four engines, two for each rotor, and no cross shafting saves about 750 lb in empty weight. Although this required the tilt wing to hover on two engines,

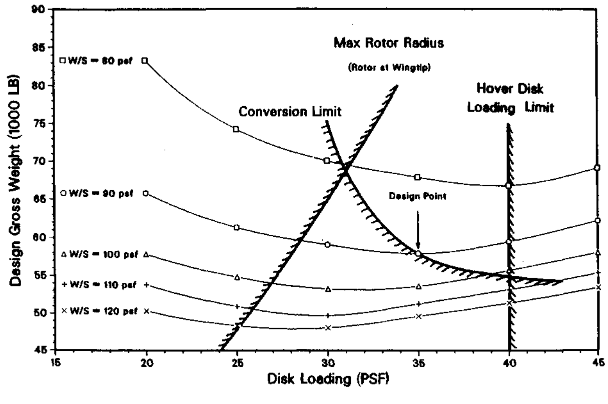

Fig. 11 Tilt wing sizing carpet plot.

Table 3 Current technology tilt wing design parameters

Gross weight	57,881 lbs
Maximum sea level power	25,645 HP SL STD
Disk loading	35 psf
Wing loading	90 psf
Aspect ratio	7.0
Hover tip speed	750 fps
Cruise tip speed	382 fps
Cruise prop efficiency	0.79
Flat plate drag	18.17
Maximum *L/D*	10.98
Cruise SFC	0.438
Dash altitude	15,000 ft
Best range alt	20,000 ft

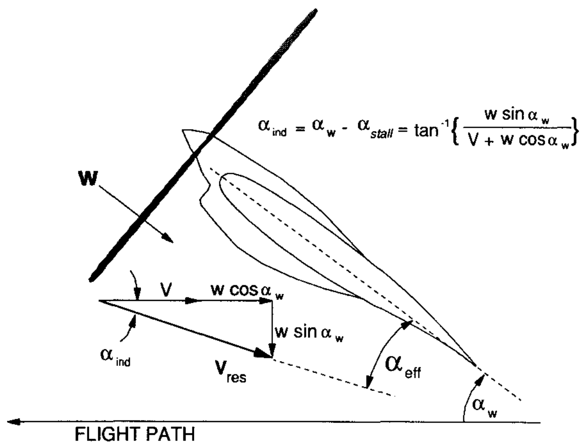

Fig. 12 Velocity diagram depicting tilt wing conversion.

one out in each nacelle, it did not increase the engine size because the cruise requirement of 450 kt still sizes the engines in this case.

Therefore, it can be concluded that cross shafting in a tilt wing configuration may not be necessary with a demanding high-speed cruise mission. The design point chosen does not represent the minimum gross weight solution. Figure 11 shows that a disk loading of 35 psf, which provides a lower downwash and increased hover efficiency, can be achieved for a small penalty in gross weight.

Conversion

Conversion from helicopter to airplane mode normally occurs while climbing. Reconversion from airplane to helicopter mode occurs while descending. Since descending flight requires less thrust, and delaying wing stall depends on the downwash from the rotors, reconversion while descending establishes the critical wing-rotor relationship.

As the wing rotates, it experiences angles of attack from 0 to 90 deg if isolated from the rotors. The downwash from the rotors provides a velocity component which causes the resultant angle of attack to be reduced. Figure 12 shows the wing at an incidence angle that is greater than the stall angle of the wing. The rotor slipstream induces a velocity tangent to the wing which depends on disk loading, freestream velocity and rotor angle of attack (assumed equal to the wing incidence angle). The governing equation which describes the induced angle at the wing in terms of rotor induced velocity, wing incidence and freestream velocity appears in the figure. For the wing to remain unstalled, the induced angle must at least be equal to the difference between the wing incidence and the wing stall angle.

Examination of the equation in Fig. 12 shows that for a given wing angle, only two approaches can generate the required induced angle at the wing: 1) an increase in the rotor downwash, either by an increase in thrust or disk loading; and/or 2) decreasing the freestream velocity. Chord-to-diameter ratio, c/D, the classic ratio used to describe the required relationship between the rotor and the wing, appears nowhere in the equation, and therefore, by itself represents no inherent limit. The downwash velocity appears in both the numerator and the denominator, whereas the freestream velocity appears only in the denominator. Reducing the freestream velocity and/or increasing the downwash velocity represents the two means of keeping a given wing unstalled.

The preferred low disk loading rotor induces smaller velocities at the wing which adversely affects conversion. However, using high-lift devices on the wing enables a reduction in stall speed (freestream velocity) and adds induced drag which requires an increase in thrust (induced velocity) to overcome. The idea of using high-lift devices to increase descent capabilities has been substantiated by experimental investigations.[8,9]

The results of the conversion study indicate that wing loading to disk loading (for aircraft with similar high-life systems) is the appropriate parameter which determines descent performance. The limiting ratio depends on the high-lift system. This is contrary to a widely accepted understanding that some fixed value of c/D (which is a form of wing loading to disk loading) determines descent performance.

Technology Trade Studies

Like the matrix created for the rotor/wing, a brainstorming session provided the technology matrix shown in Table 4 for the tilt wing. Figure 13 shows the areas where new technologies can be applied to the tilt wing. The same measures of effectiveness applied to the rotor/wing were used to assess the impact of the technologies listed for the tilt wing. Figure 14 shows the effect of each technology application on the tilt wing measures of effectiveness.

Table 4 Tilt wing advanced technology goals

Technology	Tilt wing
Materials and structure	Overall weight (−15% Primary structure) (−10% Secondary structure)
Propulsion	IHPTET Goals (−35.5% SFC, +100% P/W) Cruise efficiency (+8.3% Cruise efficiency)
Drive train	ART Goals (−20% Gear box weight) (−25% Driveshaft weight)
Aerodynamics	High drag divergence (M_{DD} = 0.75) Increase conversion wing Loading (120 psf)
Flight controls	Reduce empennage size (−15% Area) Reduce weight (−10%)
Subsystems	Reduce weight (−10%)

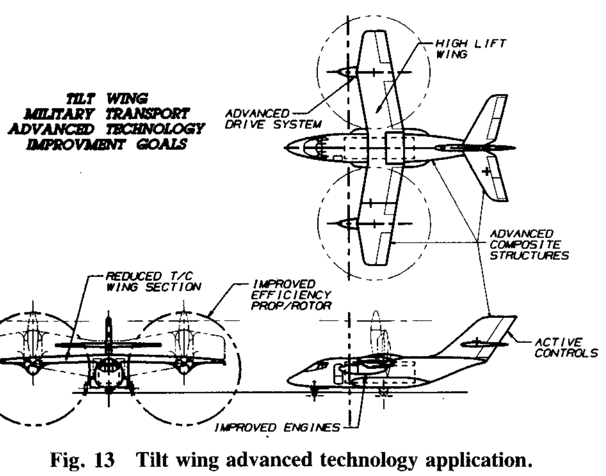

Fig. 13 Tilt wing advanced technology application.

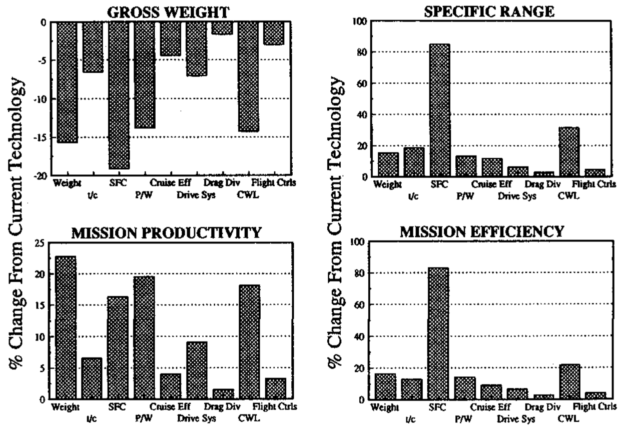

Fig. 14 Results of technology application to tilt wing.

Gross Weight

Like the rotor/wing, Fig. 14 shows that the phase III IHPTET reduction in SFC has the greatest impact on tilt wing gross weight. The engine power-to-weight increase makes an even larger contribution for the tilt wing than for the rotor/wing because of the direct influence on the tilt wing drive system, which is the single largest component of the empty weight. Just a reduction in the drive system weight alone (application of advanced rotorcraft transmission goals) reduces the gross weight more than 6%. These observations bring into focus the very important role that drive system weight plays in rotor-driven high-speed concepts.

Technologies applied to the wing, wing thickness reduction (with no relative weight increase), wing area reduction, and drag divergence Mach number increase, account for a large decrease in tilt wing gross weight. It is mainly due to reductions in drag which correspond to lower fuel required for the mission. This is more important for the transport mission which has longer and faster cruise segments than the ground attack mission. The relatively low impact of increasing wing drag divergence results because the wing never reaches the drag divergence boundary at any point during the mission.

The reduction in wing area needed for conversion accounts for the most significant decrease in drag. This is reflected in the large decrease in gross weight. Additionally, the reduction in wing area corresponds to a significant reduction in vehicle empty weight. Figure 14 indicates that a reduction in wing area has the third largest impact on gross weight, and an even larger effect on mission efficiency and specific range. For these reasons, reducing wing area represents the potential for high payoff in vehicle effectiveness.

The two remaining areas of technology are prop/rotor cruise performance and empennage reduction through active flight controls. The cruise propulsive efficiency increase of 8.3% show a small but significant decrease in gross weight. This technology represents the application of advanced prop/rotor planform, tip shaping, and coaxial rotor. The reduction in empennage size reflects only a small change in gross weight when compared to the application of other technologies.

Mission Productivity

As expected, Fig. 14 shows that mission productivity increases significantly through the application of advanced structures, the increases in engine power-to-weight ratio, and the reduction in wing area. These advances all reflect direct reductions in vehicle empty weight. Aside from the reduction in empennage size, the remaining areas of technology increase mission productivity through indirect empty weight reduction. Like the rotor/wing, the reduction in SFC has such a large effect on gross weight that the empty weight is significantly reduced.

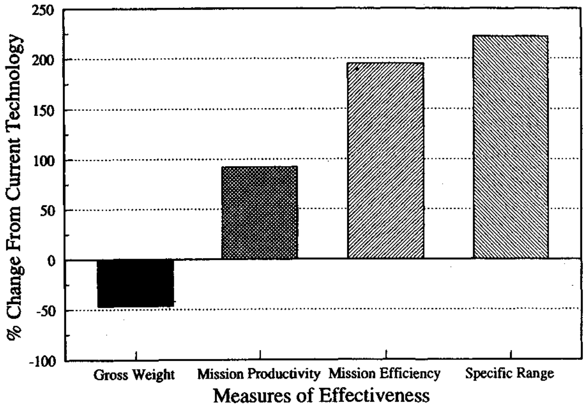

Fig. 15 Effect of combined technology application on tilt wing effectiveness.

Mission Efficiency

Figure 14 shows that the reduction in SFC is, by far, the largest contributor to increased mission efficiency. Surprisingly, the reduction in conversion wing loading is the next largest contributor to increased mission efficiency. The reduction in wing thickness also shows a significant improvement. This, unlike the rotor/wing, shows the large impact on mission fuel required by drag reduction. This is due to the differences in the ground attack and transport mission. As described above, the increased cruising range and speed magnifies the importance of drag reduction. The main conclusion drawn from the mission efficiency graph in Fig. 14, therefore, is that reductions in drag are more significant than weight savings due to advanced structures.

Specific Range

The specific range graph in Fig. 14 resembles the mission efficiency graph very closely. This is more the case for the tilt wing than for the rotor/wing due to a more cruise-intensive mission and the fact that decreases in conversion wing loading do not effect hover performance significantly. The only difference between the two graphs is that the application of advanced structures and materials affects the mission efficiency more than wing thickness reduction, and vice versa for the specific range. This results because specific range depends mainly on cruise drag, while mission efficiency relies on cruise drag and hover performance.

Combined Results

Figure 15 shows the effect of applying all of the technologies simultaneously to the tilt wing compared to the baseline vehicle. The application of all of the technology areas to the tilt wing transport result in almost a 50% weight reduction. When the effect on mission productivity, mission efficiency, and specific range are considered, the future potential of the tilt wing as a military transport is very promising. This is accentuated when considering the enormous short takeoff potential of the tilt wing.

Conclusions

The renewed interest in high-speed rotorcraft introduces the possibility of revisiting proven concepts and developing new concepts. Advances in technology since the 1950s and 1960s make concepts flown during this time more viable today. Concepts such as the tilt wing with its integrated propulsion system, remains relatively simple, although, increasing flight speeds above 350 kt significantly increases its complexity. Technology available by the year 2005 will increase the effectiveness of all concepts, including helicopters and fixed-wing aircraft. New concepts, capable of high-cruise speeds, will become feasible as long as enabling technologies are developed. In addition to performance gains, emphasis on reliability, public acceptance issues, maintainability, and transportation infrastructure development, must be addressed concurrently if high-speed rotorcraft are to become reality.

The tilt wing concept appears very competitive with the tilt rotor, especially for a transport mission. The tilt wing's performance reflects a compromise between the conversion characteristics and cruise requirements. Past examples of the concept sacrificed cruise wing loading for reasonable conversion characteristics. This resulted in much more wing than desired for efficient cruise flight. Increasing the cruise wing loading would significantly improve the cruise efficiency and leads to greatly reduced gross weight. Tilt wing literature repeatedly suggests that the use of high-lift systems can reduce the wing area required for conversion.

The rotor/wing, while never flown, represents a concept that could provide leap ahead capabilities in the high-speed rotorcraft field. It requires no new engine technology, although it benefits (as do other concepts) from advances in engine technology. It uses integrated lift and propulsion systems which benefits it through reduced weight and drag. The reaction drive system removes a major item of weight from the vehicle, the transmission. The absence of a transmission also significantly reduces maintenance and acquisition costs. Wind-tunnel testing in the 1960s demonstrated the feasibility of the concept through conversion and transonic fixed-wing flight. Studies indicate that significant benefits can be gained through configuration changes which reduce the size of the centerbody required for conversion. This concept, too, will benefit from additional development and represents the opportunity for significant payoff in mission effectiveness.

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