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Selected Design Issues of Some High-Speed Rotorcraft Concepts

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A study of vehicle concepts for high-speed rotorcraft applications has been undertaken at Ames Research Center with the objective of defining their technology needs. The design guidelines include a low downwash velocity in hover, good low-speed maneuver capabilities, and cruise speeds up to 450 kt. Four contractors and a systems analysis effort within NASA have defined promising configurations which may be capable of meeting these goals. This article addresses challenging problems associated with some of the configurations in the areas of aerodynamics, propulsion, weights, and aeroelastic stability.

Nomenclature

A = total aircraft disk area
AR = wing aspect ratio
b = wing span
C_{d_w} = drag coefficient of parts which scale with the wing
C_f = skin friction coefficient based on the square-cube law, Eq. (10)
C_L = aircraft lift coefficient
C_T = thrust coefficient, rotor
c = wing section chord
$\bar{c}$ = mean aerodynamic chord
D = aircraft drag, rotor diameter
dQ = blade element torque
dT = blade element thrust
e = Oswald efficiency factor
f = flat plate drag area of parts which do not scale with the wing
h = altitude
k = ratio of fuselage width-to-wing span
L = aircraft lift
M = Mach number
q = dynamic pressure
R = rotor radius
S = wing planform area
S_{opt} = wing planform area giving maximum lift-to-drag
t = wing section maximum thickness
v = cruise airspeed
W = aircraft gross weight
W_e = aircraft empty weight
w = fuselage width plus propeller tip clearance
x = blade station, r/R
η_e = blade element efficiency
ν = rotor induced velocity
σ = rotor solidity
ϕ = inflow angle
Ω = rotor angular rotation rate

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Introduction

OVER a decade of experience with the XV-15 has given sufficient credibility to the tiltrotor aircraft to result in the design and testing of a production aircraft, the V-22 Osprey. Tiltrotors are faster than helicopters (270–300 kt) with disk loadings somewhat higher (17–22 psf).

A natural extension of this capability is to increase the cruise speed while preserving the low disk loading. In his 1987 AHS Nikolsky lecture, Drees[1] reviewed the potential for some high-speed rotorcraft (HSRC) concepts. He concluded that "speeds will almost certainly be increased to the 450 knot level." This high speed is felt to be near the upper limit of proprotor driven concepts, and so became a guideline for NASA research.

In 1986, NASA Ames Research Center made a decision to examine concepts for a high-speed, low-disk loading rotorcraft in the light of new technology. A statement of work was written that became the basis for the award of four study contracts[2-5] to industry to define the technology needs of high-speed rotorcraft. NASA Ames also initiated its own mission analysis effort to begin investigating promising concepts in parallel with the industry studies, and to address some of the fundamental problems associated with high-speed, low-disk loading rotorcraft. This work has now expanded to investigations of tiltrotor, tilt wing, folding tiltrotor, and two NASA Ames concepts: 1) the coaxial folding tiltrotor, and 2) a stopped rotor concept (M-85). The industry studies and the in-house efforts have identified some promising concepts and some of the technical issues associated with these concepts.

This article is divided into three sections. In the first section, the high-speed rotorcraft concepts we are considering are briefly described. In the second section, several important technical issues are investigated in some detail. These are design, mission, scale, and configuration effects on empty weight, cruise lift-to-drag ratio (L/D), and high-speed proprotor efficiency. In the last section, some important design constraints are discussed.

Concepts

Artist concept renderings of the aircraft concepts being considered by one or more of the contractors, or by NASA, are shown in Figs. 1–3.

The folding tiltrotor (Fig. 1) is believed to have the highest speed potential of all the concepts. For reasonable weight and size, it will require a convertible engine and offers some relief in terms of rotor design: the rotor is not used for propulsion at very high speeds. A variation on this idea, the coaxial propfan/folding rotor (Fig. 1) is a NASA concept which uses a rotor for hover and a geared propfan for propulsion in high-speed flight, and therefore, does not need a convertible engine.

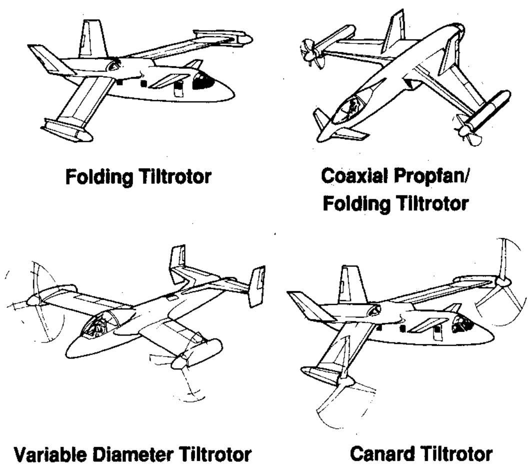

Fig. 1 Tiltrotor concepts.

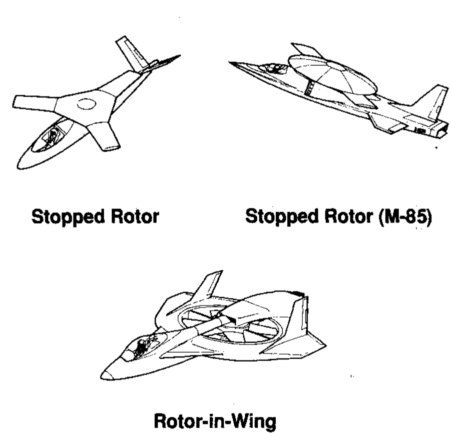

Fig. 2 Stopped rotor concepts.

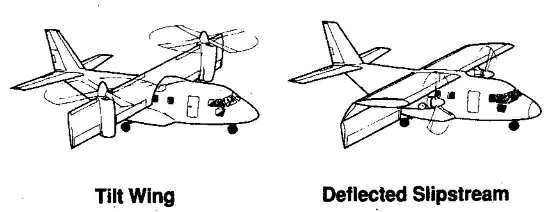

Fig. 3 Variable wing concepts.

Two other kinds of tiltrotors have been chosen for investigation: 1) a canard tiltrotor and 2) a variable diameter tiltrotor (Fig. 1). The variable diameter tiltrotor may be able to deal more effectively with the difficult compromises required of a rotor in hover and at high-forward speed. The canard tiltrotor uses swept-forward wings to deal with airframe compressibility, and therefore, avoids the weight and complexity of folding mechanisms and convertible engines. To meet the high-speed requirements, proprotors for such concepts may require novel blade planforms incorporating sweep, high-twist, and sections with low-thickness/chord ratios. The variable diameter tiltrotor deals with the difficult compromises required of a rotor in hover and a high forward speed in a different way, offering low disk loading in hover and moderate tip speeds in cruise without the need of rpm reduction.

The stopped rotor (Fig. 2) is similar in concept to the rotorwing advocated by Hughes in the 1960s. The large rotor hub fairing acts as a low-aspect ratio wing and unloads the rotor during conversion. Even though it has a fairly low-aspect ratio, it has the potential for a tip drive system which eliminates the transmission and cross shafting. A variant of this (M-85) is being investigated at NASA Ames (Fig. 2).

The rotor-in-wing concept (Fig. 2) is among the least studied and most unusual concepts considered. It has some desirable attributes for a military mission, among them potential for low observability and the ability to maneuver in confined spaces without fear of rotor strikes. The ducted fan arrangment has the effect of decreasing the apparent disk loading. Problems include aerodynamic pitch-up and low L/D in cruise.

The tilt wing (Fig. 3) uses conventional propellers and, therefore, historically has had a higher disk loading and higher cruise speed than other rotorcraft concepts. Problems include wing stall under approach flight conditions. This, in turn, constrains the disk loading.

Finally, the deflected slipstream concept (Fig. 3) was wind-tunnel tested and flight tested in the 1960s. It has the advantage that the rotor, gearbox, and engine do not rotate during conversion. One problem that has not been solved is large pitch trim changes in ground effect.

Technical Issues

The gross weight of an aircraft for fixed mission parameters (range, payload, hover time) can be estimated using simplified models. These methods use average, historical values for the key factors influencing fuel required, such as specific fuel consumption (SFC), propeller efficiency, empty weight fraction, and vehicle L/D. Results of one form of this analysis are presented in Fig. 4. It shows the variation of gross weight/payload fraction as a function of vehicle empty weight fraction and overall L/D.

It is interesting to examine current technology values of the key parameters which govern mission gross weight. Efficient transport aircraft have empty weight fractions near 0.55 and maximum L/D values of about 16. The only example of a current technology tiltrotor aircraft, the V-22, has a substantially greater empty weight fraction and significantly smaller L/D (<10), which means that much larger vehicles will be needed for equivalent fixed wing payloads. Of course, a significant operational benefit must be associated with the VTOL capabilities of these aircraft: either shorter block times, smaller and more accessible VTOL ports, or some kind of military advantage such as rescue capability.

Empty Weight Fraction

A variety of production and experimental VTOL aircraft empty weight fractions are shown sorted by empty weight fraction in Fig. 5. The sorting, or ranking by W_e/W roughly divides the types into three groups: 1) experimental VTOL aircraft, 2) some fighters and more efficient VTOL types, and 3) efficient pure helicopters. The experimental group have weight fractions exceeding 0.75 and are not representative of potential efficient high-speed concepts. The next class includes the AV-8B, the V-22, and the XC-142 with W_e/W around 0.65. The lighter aircraft are mostly efficient helicop-

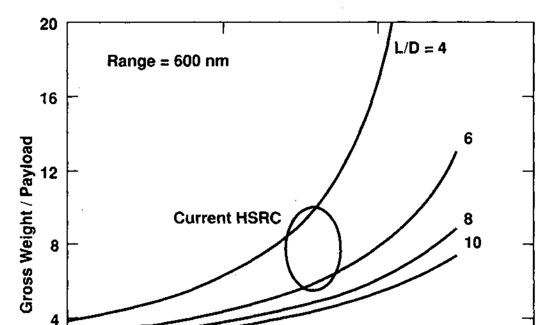

Fig. 4 Payload weight fraction as a function of empty weight fraction and vehicle L/D.

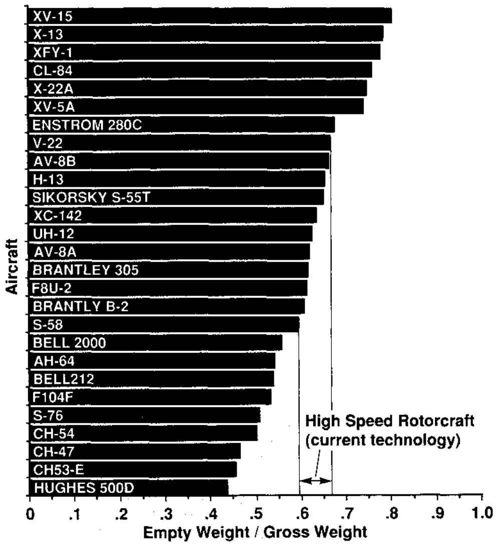

Fig. 5 VTOL Aircraft sorted by empty weight fraction.

tors with weight fractions as low as 0.45 (Hughes 500). Even though this is a coarse comparison, it can be anticipated that fractions around 0.65 are the best that can be achieved with current technology. Certainly they will exceed the figure for efficient fixed wing transports of 0.55 if cross shafting and heavy transmissions are inherent to the concept.

Lift-to-Drag Ratio

It can be seen from Fig. 4 that great improvements can be made by increasing aircraft L/D. Figure 4 also shows that as empty-to-gross weight increases, the L/D becomes even more important. L/D can be increased by reducing wetted area, reducing the skin friction coefficient, and sizing the wing so that the maximum L/D is achieved at the desired cruise altitude and airspeed.

As VTOL cruise speeds are increased to 450 kt, smaller wings are required to achieve the maximum L/D in cruise. Low-hover downwash velocities, on the other hand, require a relatively large rotor disk area. These two independent requirements, 1) a small wing for cruise and 2) a large rotor for hover, sometimes conflict because of a configuration-dependent constraint which links the wing area to the rotor disk area. This configuration constraint can force a tradeoff between the desire for high lift-to-drag in cruise and low downwash in hover.

In order to examine this tradeoff, this section will develop a simple drag equation that is accurate to first-order, use this equation to optimize the wing, examine configuration specific constraints, and discuss the effects of varying speed, altitude, aspect ratio, and fuselage drag on the obtainable L/D.

Note that the purpose here is to examine, at a basic level, the effect of aerodynamics, cruise requirements, configuration, and scale on the cruise L/D. No attempt is made to actually size vehicles in detail for a common mission accounting for all important parameters at once. Rather, the goal is to isolate the effect of each fundamental parameter to discover and understand fundamental bounds on the attainable L/D of high-speed rotorcraft. To this end, relatively large variations from a reasonable baseline are made in each important parameter.

Analysis of Lift-to-Drag

In the standard equation for the drag of an aircraft, the parasite drag is assumed to be proportional to the wing area. However, a large portion of an aircraft's parasite drag is actually due to nonlifting wetted area such as the fuselage, nacelles, and sponsons. This portion of the parasite drag will be called the flat plate drag and is not proportional to the wing area. For the DC-9-30, 45% of the parasite drag is flat plate drag by this definition. For VTOL aircraft, an even greater percentage of the parasite drag is typically flat plate drag. For example, about 79% of the V-22 parasite drag is flat plate drag.

This suggests that the parasite drag should be separated into two terms: 1) parasite drag which is fixed and independent of the wing area, and 2) parasite drag which is proportional to the wing area. As stated before, the first term will be called the flat plate drag. The second term will be called the scaled drag, and it includes the drag of the horizontal and vertical tail because the planform area of these surfaces is normally proportional to the wing area.

Following this reasoning, the total drag of an aircraft may be written as

$$D = fq + C_{d_w}qS + (C_L^2/\pi eAR)qS \qquad (1)$$

The expression for total aircraft L/D is then given by Eq. (2)

$$(L/D) = [(fq/W) + (C_{d_w}qS/W) + (W/\pi eARqS)]^{-1} \qquad (2)$$

The value of wing area to maximize L/D with everything else in Eq. (2) fixed, and the maximum possible L/D, are obtained analytically as

$$S_{\text{opt}} = \frac{W}{q\sqrt{C_{d_w}\pi eAR}} \qquad (3)$$

$$\left.\frac{L}{D}\right|_{\max} = \left[2\sqrt{\frac{C_{d_w}}{\pi eAR}} + \frac{fq}{W}\right]^{-1} \qquad (4)$$

Note that this is a different optimum than that obtained when wing area is fixed in Eq. (2) and dynamic pressure is allowed to vary.

Two points should be noted about the optimum [Eqs. (3) and (4)]. The first point is that the optimum wing area is not a function of the flat plate drag term. This means the wing can be sized knowing only the scaled drag and without knowing the flat plate drag. The second point is that the maximum lift to drag obtained with the optimum wing area is a function of the dynamic pressure. This means, e.g., that increasing the required cruise altitude with true airspeed held constant, increases the maximum L/D (well-known by fixed wing transport designers).

Configuration Constraints on Wing Area and Disk Area

Considerations such as reasonable fuel efficiency in hover, the ability for people to work in the downwash of the rotor, reasonable autorotation sink rates, and problems with ground erosion, blown debris, and engine ingestion of debris may limit acceptable disk loadings of high-speed rotorcraft.

If, in a particular configuration, the wing must interact with the rotor, this required interaction may prevent simultaneously sizing the rotor for the hover requirement and sizing the wing for maximum L/D [Eq. (3)]. In that case, either the hover requirement must be relaxed or a poor cruise L/D must be tolerated.

The required interaction between a wing and rotor can take many forms. It may be geometric, such as when the rotor is attached to the wing, or it may be aerodynamic, such as when the wing must deflect the rotor wake. Whatever this required interaction, it forms a hard, configuration-dependent link between the wing area and the disk area. The designer cannot choose one of these important design variables without constraining the other.

This may be seen by introducing the configuration constraint variable S/A, the ratio of wing area to disk area. A key point is that S/A is configuration-dependent and cannot be chosen arbitrarily. Substituting this relation into Eq. (2) yields Eq. (5):

$$\frac{L}{D} = \left[\frac{fq}{W} + \frac{C_{d_w}q(SA)}{W/A} + \frac{W/A}{\pi eARq(S/A)}\right]^{-1} \tag{5}$$

As examples of how the wing area can be linked to the disk area, we will consider tiltrotors, tilt wings, and deflected slipstream aircraft. However, this phenomenon is not limited to just these three configurations. Most VTOL configurations have some requirement which links the wing area to the disk area.

The behavior of high-speed rotorcraft L/D is illustrated in Figs. 6–9. Figures 6 and 7 examine the effect of flight conditions (airspeed and altitude) on L/D. Figures 8 and 9 show the effects of important aircraft design changes (flat plate drag and aspect ratio) on L/D. Before these figures are presented, however, we will discuss the baseline case and the wing sizing constraints for each of the three configurations.

Baseline Case

The baseline flight conditions, drag levels, and geometry (which are noted in boxes on each figure) are representative of an advanced high-speed rotorcraft on a transport mission.

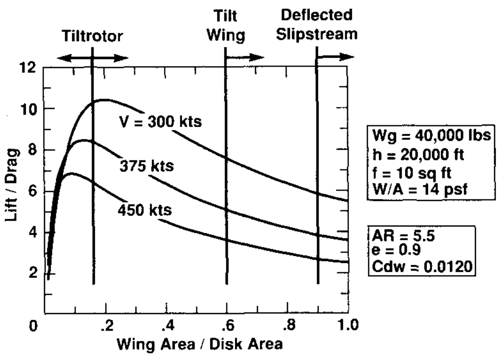

Fig. 6 Effect of airspeed on L/D.

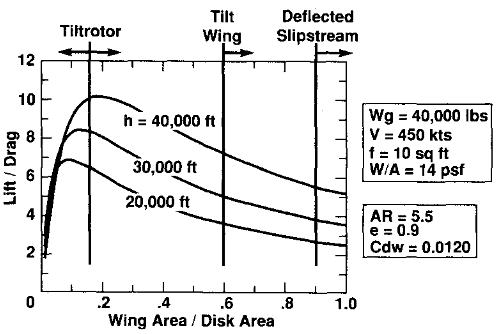

Fig. 7 Effect of altitude on L/D.

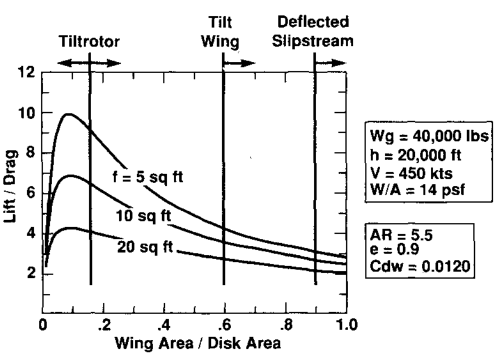

Fig. 8 Effect of flat plate drag on L/D.

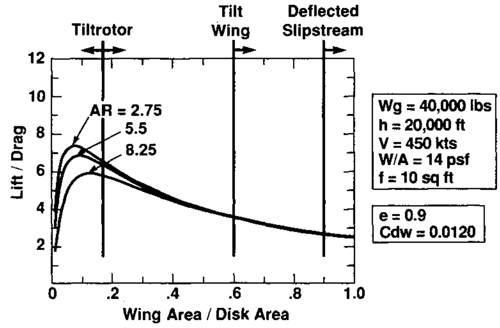

Fig. 9 Effect of aspect ratio on L/D.

The baseline cruise speed is 450 kt, which is our goal for high-speed rotorcraft. The gross weight of 40,000 lb is reasonable for a 6000-lb payload (≈30 passengers). The cruise altitude of 20,000 ft is reasonable given the relatively low drag-divergence Mach numbers of plausible high-speed rotorcraft. The fuselage drag area of 10 ft^2 is representative of a clean 40,000-lb VTOL aircraft.[6] The aspect ratio of 5.5 is typical of tiltrotor aircraft. The wing drag coefficient of 0.0120 includes the additional drag of the horizontal and vertical tails, assuming these surfaces increase the planform area by 50% of the wing planform area.

If one restricts the maximum wake velocity to hurricane conditions (75 mph), this results in disk loadings less than 14 psf. This also corresponds to a 260-ft-lb peak overturning moment of a 6-ft man for a 40,000-lb single-rotor vehicle. Wernicke[7] recommends this overturning moment as a practical limit if personnel must be able to work anywhere underneath the rotor(s). For this analysis, 14 psf will be used as the disk loading requirement.

Tiltrotor Wing Sizing

The geometric constraint that connects the wing area to the disk area for a tiltrotor is that the center of the rotor is attached to the wing tip. For a given aspect ratio and fuselage width, this constraint fixes the ratio of wing area to disk area:

$$b = D + kb, \qquad k = w/b \tag{6}$$

Using the definition of aspect ratio and disk area, we can derive the ratio of wing area to disk area solely in terms of aspect ratio:

$$(S/A) = [2/\pi(1 - k)^2 AR] \tag{7}$$

For typical numbers, $AR = 5.5$, $k = 0.15$, then $S/A = 0.16$. This constraint appears as a vertical line labeled "tiltrotor" on Figs. 6–9.

Tilt-Wing Wing Sizing

For tilt wing aircraft, the wing must have a large enough chord to avoid stall and buffet during landing approach. This constraint has been expressed as a minimum chord-to-diameter ratio of about 0.4.[8] In addition, the wing must be completely immersed in the prop wash. For tilt wings with two propellers, this constraint may be expressed as

$$b = 2D + kb, \qquad k = w/b$$
$$\left.\frac{\bar{c}}{D}\right|_{\min} = 0.40 \tag{8}$$

Using Eq. (8), we can derive the ratio of wing area to disk area in terms of the minimum chord-to-diameter ratio:

$$\frac{S}{A} = \frac{4}{\pi(1 - k)} \times \left.\frac{\bar{c}}{D}\right|_{\min} \tag{9}$$

For typical numbers

$$k = 0.15, \quad \frac{\bar{c}}{D}\bigg|_{\min} = 0.40$$

then

$$S/A = 0.60$$

This constraint appears as a vertical line labeled "tilt wing" in Figs. 6–9.

Deflected Slip-Stream Wing Sizing

For deflected slip-stream aircraft, the wing must be large enough to turn the rotor wash approximately 80 deg. This constraint has been expressed as a minimum chord to diameter ratio of about 0.6.[9] Also, the wing must be completely immersed in the prop wash, as was the tilt wing. The constraint is exactly the same as for the tilt wing [Eq. (9)] except for the value of the minimum chord-to-diameter ratio. For typical numbers

$$k = 0.15, \quad \frac{\bar{c}}{D}\bigg|_{\min} = 0.60$$

then

$$S/A = 0.90$$

This constraint appears as a vertical line labeled "deflected slipstream" in Figs. 6–9.

Effect of Airspeed and Altitude on L/D

Equation (3) shows that as the required cruise dynamic pressure increases, the optimum wing area decreases. This means that as one tries to go faster or lower in the atmosphere, the wing should get smaller. Assuming that the rotor size is fixed by hover requirements, the ratio of required wing area to required disk area also decreases.

Figures 6 and 7 shows this graphically. Each *L/D* curve is calculated from Eq. (5) with the wing area tied to the disk area through the configuration constraint (*S/A*) and the disk loading fixed at 14 psf. Figure 6 shows three cruise airspeeds and Fig. 7 shows three cruise altitudes.

Both figures show similar trends. As cruise airspeed is increased or cruise altitude reduced, the maximum *L/D* drops from 10 to less than 7, the optimum *S/A* drops from 0.2 to 0.1, and the entire *L/D* curve is lowered for *S/A* greater than optimum. The large reduction in *L/D* is primarily due to increased dynamic pressure acting on the flat plate drag.

Figures 6 and 7 also show that tiltrotors fall near the peaks of the *L/D* curves, whereas tilt wings give up about $\frac{1}{3}$ of their potential *L/D* and deflected slipstream aircraft give up about $\frac{1}{2}$ of their potential *L/D*. If one is unwilling to compromise the disk loading constraint (14 psf), this represents a fundamental difference in the *L/D* potential of each configuration at the desired cruise speed of 450 kt.

It should be noted that increasing altitude increases Mach number for a constant true airspeed (such as 450 kt). Typically, the compressibility drag rise is very sensitive to Mach number, and in a more complete analysis this drag rise will limit the cruise altitude. This means that unless the drag divergence Mach number of advanced rotorcraft are comparable to fixed wing transports, the optimum cruise altitude will be lower and the maximum *L/D* will consequently be reduced.

Effect of Flat Plate Drag and Aspect Ratio on L/D

Equation (4) shows that flat plate drag and wing aspect ratio have first-order effects on the maximum achievable *L/D*. The extent to which these variables may benefit *L/D* depends on the relative contributions of the wing and fuselage to drag, and how close the aircraft is operating to the optimum *L/D*.

Figure 8 plots the effect of varying flat plate drag on *L/D*. As before, each *L/D* curve is calculated from Eq. (5). The lowest drag (5 ft^2) is that of a very clean jet aircraft, and represents a lower bound on what can be achieved for a high-speed rotorcraft. The middle drag (10 ft^2) is that of a clean tiltrotor aircraft and is taken from Ref. 2. The high drag (20 ft^2) is representative of current tiltrotor technology for military applications.

Figure 8 shows that reducing the flat plate drag of advanced rotorcraft has a dramatic effect on *L/D* if the wing is sized correctly. On the other hand, if the wing is too large, the *L/D* will be relatively poor regardless of the flat plate drag. In particular, the tilt wing and deflected slipstream aircraft are showing cruise *L/D* less than half the tiltrotor. Even if these configurations achieve large reductions in flat plate drag over the tiltrotor, they will probably still have lower *L/D* if the 14 psf disk loading constraint is not relaxed.

Figure 9 plots the effect of varying aspect ratio on *L/D*. As before, each *L/D* curve is calculated from Eq. (5). The baseline aspect ratio (5.5) is varied 50% up and down.

This figure shows that at the quite plausible flat plate drag area of 10 ft^2 the aspect ratio has a small effect on *L/D*, and only if the wing is close to the optimum size. However, if the flat plate drag is reduced (which is desirable), then the wing aspect ratio will become more important. In other words, the relatively high flat plate drag is masking the scaled drag. If the flat plate drag is reduced, then further improvements will require reducing the scaled drag.

Effect of Scale on L/D

Part of the reason that advanced rotorcraft concepts are unlikely to match *L/D* values of transports is attributable to size, and this is a common difficulty with all smaller aircraft whose primary cargo is people. The DC-10 has a maximum *L/D* of about 16, but when scaled down to a 10,000-lb aircraft, the fuselage becomes too small for the average human passenger (Fig. 10). Even if the fuselage could be scaled down, the parasite drag would still be greater because of the lower Reynolds number, and therefore, increased drag coefficient.

L/D values of production aircraft illustrate current technology. Classes of aircraft show an improving weight-to-drag ratio with gross weight,[10] based on the parameter

$$C_f = (f/W^{2/3}) \tag{10}$$

which scales the flat plate drag according to the square-cube law.

If a constant value of *Cf*, as defined above, is associated with a class of aircraft, and if this constant is rearranged to correspond to the fuselage drag contribution term $W/(fq)$ in Eq. (2), then classes of aircraft can be compared on the basis of gross weight-to-fuselage drag (W/D) as shown in Fig. 11. *W/D* is the lift-to-drag ratio in level flight excluding the wing

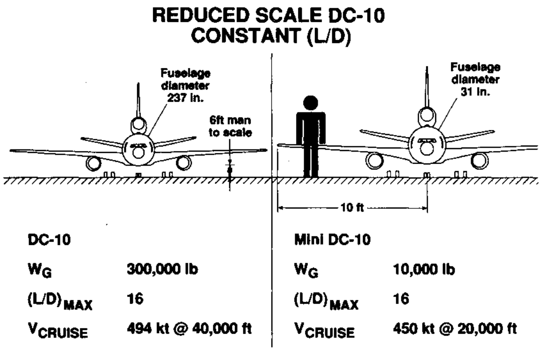

Fig. 10 Scaling effect on fuselage diameter for a large fixed wing transport.

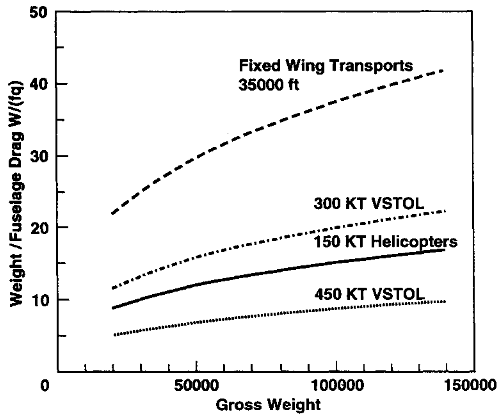

Fig. 11 Variation of gross-weight-to-fuselage-drag ratio with gross weight.

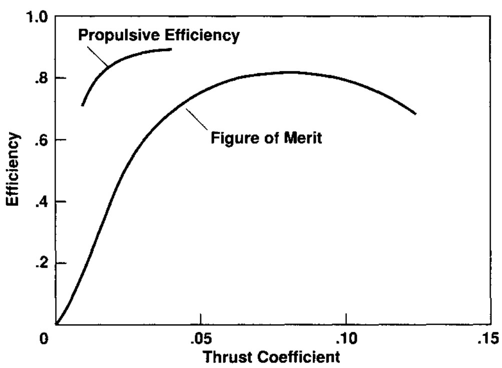

Fig. 12 Figure of merit vs thrust coefficient, XV-15 rotor.

drag. It is a measure of the cleanliness of the design with respect to flat plate drag.

W/D ratios of efficient fixed wing transports greatly exceed current technology VSTOL aircraft, due to both design requirements and the more efficient cruising altitudes of the transports. W/D values for helicopters are shown for reference. If the drag values of the 300-kt VSTOL curve are increased to reflect increased cruise speeds of 450 kt, then the values of W/D will be reduced as shown in the lowest curve. The effect of scale is seen as an improved ratio of W/D as W increases, driven primarily by increasing Reynolds number with weight.

Propulsive Efficiency of Proprotors

Concepts with propeller-rotors that are not stowed in forward flight must function efficiently as rotors in hover and then give acceptable propulsive efficiency as propellers. Efficiency of the rotor or propeller depends partly on the ability to operate all spanwise elements of the rotor at a high section L/D. Twist, RPM variation, and section thickness are major variables available to the designer to help maintain efficiency. This section discusses efficiency in terms of section L/D.

The XV-15's nondimensional rotor performance is typical of a low solidity current technology rotor. In forward flight (Fig. 12) the blade loading for best efficiency is largely independent of advance ratio; however, it is different than that required for best figure of merit in hover. The rotor thrust must vary from about W in hover, to $W/(L/D)$ in cruise. At constant tip speed, this leads to an increase in profile power and a reduction in efficiency. To avoid this, usual practice is to slow the rotor in forward flight. At higher forward speeds, a further reduction in rpm is required due to the onset of compressibility. However, the reduction in rpm results in very high inflow angles which in turn can result in low efficiencies.

If the blade element efficiency in forward flight is defined by

$$\eta_e = \frac{dT \cdot V}{dQ \cdot \Omega} \tag{11}$$

then a resolution of these forces into element lift and drag through the inflow angle φ results in an expression for blade element efficiency.

$$\eta_e = \frac{[1 - \tan\phi(L/D)^{-1}]\tan\phi}{(L/D)^{-1} + \tan\phi} \tag{12}$$

Induced losses are included in the definition of ϕ.

Insight into spanwise variation of blade section thickness required can be obtained by inverting this equation to give the required L/D of the section for a specified blade element efficiency and noting that L/D is strongly dependent on local Mach number.

$$\left(\frac{L}{D}\right)_r = \frac{\eta_e + \tan^2\phi}{(1 - \eta_e)\tan\phi} \tag{13}$$

where

$$\tan\phi = \frac{(V + \nu)}{\Omega R x} \approx \frac{V}{\Omega R x} \tag{14}$$

A local Mach number is associated with each station and it must be possible to operate the section with the required L/D at this station. The maximum L/D at fixed M and t/c for a typical section[11] is shown as a function of C_l in Fig. 13.

Plots like these result in a family of maximum L/D vs Mach number curves at fixed t/c, as shown in Fig. 14. The required L/D to give each element an efficiency of 0.8 is shown superimposed on this plot. In order to meet the efficiency requirements, the intersections of required L/D with the airfoil

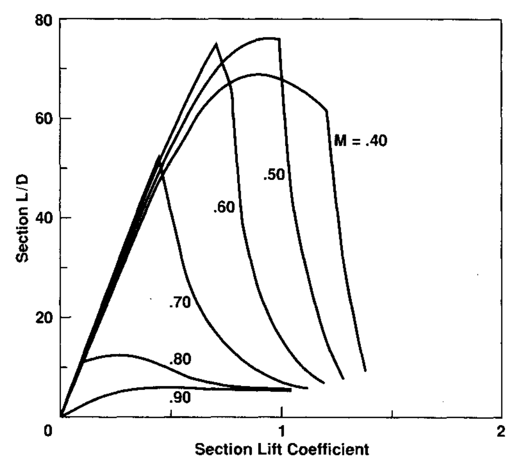

Fig. 13 Section L/D vs lift coefficient at constant values of Mach number, t/c = 10%.

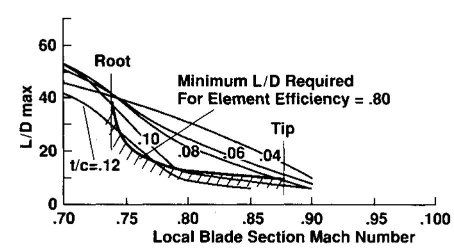

Fig. 14 Maximum section L/D vs Mach number at constant values of thickness-to-chord ratio.

characteristic curves dictate a maximum allowable blade section t/c which is a function of M. The Mach number is associated with the blade radius and flight condition. The result means that if thickness can be controlled, the aerodynamic requirements for propulsive efficiency can be met, possibly by an unswept propeller varying in thickness from 11% at the root to 6% at the tip.

Design Constraints

The foregoing has illustrated some of the aerodynamic and aeroelastic factors that will have to be considered in the design of any high-speed rotorcraft concepts. In the course of using the VASCOMP[12] sizing program, unconstrained optimizations of high-speed tiltrotors have revealed that the following constraints have significant effects on the potential gross weight of high-speed rotorcraft: 1) hover downwash velocity, 2) design Ct/σ in hover, 3) wing volume to contain mission fuel, 4) conversion acceleration and climb angle, 5) maneuver load factor, and 6) aeroelasticity.

Each of these will be discussed, and where appropriate, current values used in the NASA systems analysis studies will be noted.

Hover Downwash Velocity

In general, high-speed rotorcraft will be lighter and more efficient if the disk loading is as high as possible. The reason is that the rotor, hub, and transmission weight decrease with higher disk loading, and this trend is not offset by increases in hover fuel weight. The increase in disk loading is limited by the need for ground personnel to operate under the rotor. Overturning moment of a 6-ft man sets an allowable downwash velocity which in turn sets a maximum disk loading.

Wernicke[7] has shown that overturning moment of a man is a function of rotor size and not just disk loading. This occurs because of the relative height of the outwash boundary layer in comparison to the height of a person working under the rotor. This constraint is expressed in Wernicke's paper as a boundary of disk loading vs rotor diameter. According to his criterion, increasing the number of rotors reduces the overturning moment because the diameter is reduced without a change in disk loading. However, there is one drawback. When there is more than one rotor, the flowfield becomes directional. Compared to a single rotor with the same disk loading, the overturning moment of a multple rotor aircraft is reduced in some directions and increased in other directions.

If one takes advantage of the lowest overturning moment in such a directional flowfield by increasing the disk loading, this will introduce regions under the rotor where it is not practical to work. This leads to operational restrictions both for pilots and for personnel who must work under the aircraft. Evaluation of the flowfield under the XV-15 tiltrotor[13] which has a disk loading of 13.2 psf, led to the recommendation that "while hovering toward or over a landing site, approach the landing site into the ambient wind and ensure that ground personnel and equipment are at least 10 ft to the right or left of the landing approach centerline."

When comparing high-speed rotorcraft concepts with different numbers of rotors, it is important how directional flowfields will be treated. If operational restrictions are intolerable, then multiple rotor aircraft will be designed for their greatest overturning moment, and hence, will be penalized compared to single rotor vehicle. On the other hand, if multiple rotor aircraft are designed for their lowest overturning moment, then single rotor vehicles will be unduly penalized.

Design Ct/σ in Hover

In general, high-speed rotorcraft will be lighter and more efficient if the design Ct/σ in hover is as large as possible. Ct/σ is proportional to the average blade angle of attack. There must be some margin between the design blade angle of attack and stall during the most demanding required maneuver because of loads and stability problems at stall. Reference 2 suggests $Ct/\sigma = 0.125$ as a reasonable limit. The XV-15 tiltrotor has demonstrated a maximum $Ct/\sigma = 0.20$. This corresponds to a 60% margin above the design condition in hover. What should the Ct/σ margin above the design condition be? This is a tradeoff between performance (high Ct/σ) and maneuverability (low Ct/σ). This question deserves further study.

Wing Volume to Contain Mission Fuel

To avoid a fuel fire inside the fuselage in the event of a survivable crash, fixed wing transport aircraft have historically been designed so that all the mission fuel is in the wing. Transport helicopters have historically been designed with the fuel in the fuselage because there is nowhere else to put it. To address the fire hazard, helicopters use bladder tanks to prevent rupture in a crash. The bladder tanks have been very effective at saving lives, but there is a considerable weight penalty (bladder tanks weigh about 2.5 times integral tanks).

The XV-15 and V-22 Osprey have 23% thick wings and easily hold the required mission fuel. However, high-speed rotorcraft may need thinner wings to increase the drag divergence Mach number, and these thin wings may not contain all the necessary fuel. This brings up the question of should high-speed rotorcraft be required to have all the mission fuel in the wing? This question deserves further study.

Conversion Acceleration and Climb Angle

Practical high-speed rotorcraft need to climb and accelerate simultaneously along the departure flight path. Both of these requirements increase the power required during conversion. Also, the propulsive efficiency is often worse when partially converted than it is in either hover or cruise. Depending on the required climb and acceleration, it is possible that the engines and/or transmission will be sized by conversion. Conversion is also frequently a critical condition for rotor loads.

In order to size a high-speed rotorcraft, the minimum required acceleration and climb angle must be specified. Depending on this requirement, some configurations will do better than others. For example, tiltrotors do not have the stall problem of tilt wings during steep descents. The question of desirable conversion acceleration and deceleration deserves further study.

Maneuver Load Factor

Fixed wing attack aircraft load factors are limited by the pilot's ability to tolerate high g. Limit load factors of 7.33 g are common. Helicopters are designed to much lower load factors because the rotor cannot generate the high g that a wing can unless excessive blade area is used. Limit load factors of 2.33 g are typical.

Attack high-speed rotorcraft will be expected to maneuver at low airspeeds while partially converted. If the primary use of the aircraft is maneuvering at low speed, then designing the wing for high-speed maneuvering load factors may be an unnecessary weight penalty.

Current system studies are using 7.33 g which corresponds to the high-speed design load factor. More investigation of maneuver requirements are needed to establish a more rational criterion.

Aeroelasticity

The technical issues here are very complex, involving a balance between wing thickness, wing weight, and proprotor design details which collectively meet strength and stiffness requirements. The 450-kt cruise speed of these concepts means that compressibility is an issue. Transonic drag of the wing, but not necessarily on the fuselage and empennage, must be dealt with. The cruise Mach number is near 0.73 (450 kt at 20,000 ft). Drag divergence Mach number is strongly a function of wing t/c, and if structural criteria (aeroelastic stability and/or maneuver load factor) drive the wing thickness up, reduced aspect ratio, wing sweep, or advanced wing sections must be used to avoid compressibility effects.

Johnson et al.[6] considered performance, stability, and maneuverability using the comprehensive analytical model of rotorcraft aerodynamics and dynamics (CAMRAD) and a preliminary design and performance code to optimize and assess the feasibility of high-speed tilting proprotor aircraft. However, at present there do not seem to be any preliminary guidelines for considering the effects of aeroelasticity on high-speed configurations other than using comprehensive, multidisciplinary codes, and each concept must be examined on a case-by-case basis.

In order to extend the application of comprehensive codes to study the effects of aeroelasticity on high-speed configurations, attempts are currently being made to establish a readily available link between proprotor whirl flutter and drag-divergence Mach number in the wing weight estimation and design process. To date, there has been substantive activity in examining this link using a CAMRAD/JA[14] model of the XV-15 tiltrotor with the advanced technology blades (XV-15/ATB). The objective of this effort is to arrive at a solution to the dichotomy that exists between the increased wing drag-divergence Mach numbers and the reduced whirl flutter speed stability associated with a thin wing.

Other aeroelastic phenomenon, analyses, and solutions that have been encountered in the dynamics of advanced rotor systems have been discussed by Kvaternick[15] and Johnson.[16–18] The implications of establishing a practical relationship between these phenomenon and the wing thickness and weight calculations have not yet been examined, however, they may weigh heavily in the preliminary design, optimization, feasibility, and assessment of technology requirements of high-speed configurations.

Concluding Remarks

This article has reviewed fundamental design and mission parameters which strongly affect the efficiency of high-speed rotorcraft. These include empty-weight-to-gross-weight ratio, cruise lift-to-drag ratio, propeller efficiency, wing stiffness to prevent whirl flutter, maximum allowed hover downwash velocity, design Ct/σ, required conversion acceleration and climb angle, and required maneuver load factor. Cruise lift-to-drag ratio is in turn strongly influenced by cruise airspeed, cruise altitude, drag divergence Mach number, fuselage drag, wing area-to-disk area ratio, aspect ratio, disk loading limit, and scale.

Current technology values for empty weight, propulsive efficiency, airframe drag, etc., lead to high-mission gross weight for high-speed rotorcraft compared to fixed wing aircraft. These high gross weights reflect increases in empty weight and fuel fraction that arise from high airframe drag at high speeds or poor propulsive efficiency. In order to increase the efficiency of high-speed rotorcraft, significant improvements must be made in these areas.

Choosing among the various options will be difficult because of the variety of airframe concepts and propulsion systems under consideration. A balanced technical program should include exploratory development of the more unconventional concepts or unique technologies, as well as an extension of the more familiar or generic technology beyond current limits.

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