Performance, Loads and Stability of Heavy Lift Tiltrotors

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Abstract

Summaries of rotor performance are presented for a 124,000-lb Large Civil Tilt Rotor (LCTR) design, along with isolated-rotor and fully-coupled wing/rotor aeroelastic stability. A major motivation of the present research is the effect of size on rotor dynamics. Simply scaling up existing rotor designs to the vehicle size under study would result in unacceptable rotor weight. The LCTR was the most promising of several large rotorcraft concepts produced by the NASA Heavy Lift Rotorcraft Systems Investigation. It was designed to carry 120 passengers for 1200 nm, with performance of 350 knots at 30,000 ft altitude. Design features included a low-mounted wing and hingeless rotors, with a very low cruise tip speed of 350 ft/sec. The LCTR was sized by the RC code developed by the U. S. Army Aeroflightdynamics Directorate. The rotor was then optimized using the CAMRAD II comprehensive analysis code. The blade and wing structures were designed by Pennsylvania State University to meet the rotor loads calculated by CAMRAD II and wing loads required for certification. Aeroelastic stability was confirmed by further CAMRAD II analysis, based on the optimized rotor and wing designs.

Notation

A	rotor disk area
C_T	rotor thrust coefficient, $T/(\rho A V^2_{tip})$
D/q	airframe drag/dynamic pressure
t/c	thickness to chord ratio
T	rotor thrust
V_{tip}	rotor tip speed
W	gross weight
ρ	air density
σ	rotor solidity (ratio blade area to disk area)
ISA	international standard atmosphere
LCTR	Large Civil Tilt Rotor
OEI	one engine inoperative
SOA	state of the art

Introduction

The NASA Heavy Lift Rotorcraft Systems Investigation studied several candidate configurations of very large rotorcraft designed for the civil mission defined in Ref. 1. With gross weights in excess of 100,000 lb and speeds of 300 knots or greater, such aircraft will face severe design challenges to meet acceptable performance and safety. The Large Civil Tilt Rotor (LCTR) was the most promising design resulting from the investigation. This paper addresses the optimization and analysis of the LCTR, covering rotor and wing design and presenting results for performance, stability and loads, with emphasis on the tiltrotor's most unique feature, namely its wing.

Whirl flutter is a major technology driver for tiltrotors. Therefore, careful attention must be given to the wing design process to ensure a stable and efficient solution. The task is compounded by the impact of rotor design on whirl flutter. The rotor faces conflicting design requirements: articulated and soft-in-plane rotors have low loads but poor stability, whereas hingeless (stiff-in-plane) rotors have high loads and good stability. Gimballed rotors, as used on the XV-15, V-22 and BA-609, do not scale well to four or more blades because of kinematic constraints. Therefore, the wing and rotor cannot be designed independently of each other.

Three major sets of design requirements drive the LCTR analyses addressed here. Performance goals for hover and cruise determine the rotor design and set the wing area and maximum thickness. Loads determine rotor and wing structural designs, which must be analyzed for aeroelastic stability. Performance, loads and stability requirements for both the rotor and wing influence each other during the design process, requiring an iterative optimization process (Ref. 1). In this paper, the design approach and its implications for tiltrotor technology are divided into three general areas: rotor design, wing design for loads, and coupled wing/rotor aeroelastic stability (whirl flutter). Rotor design optimization is covered in detail in Ref. 2 and is summarized herein; wing design for loads and stability are covered in greater depth.

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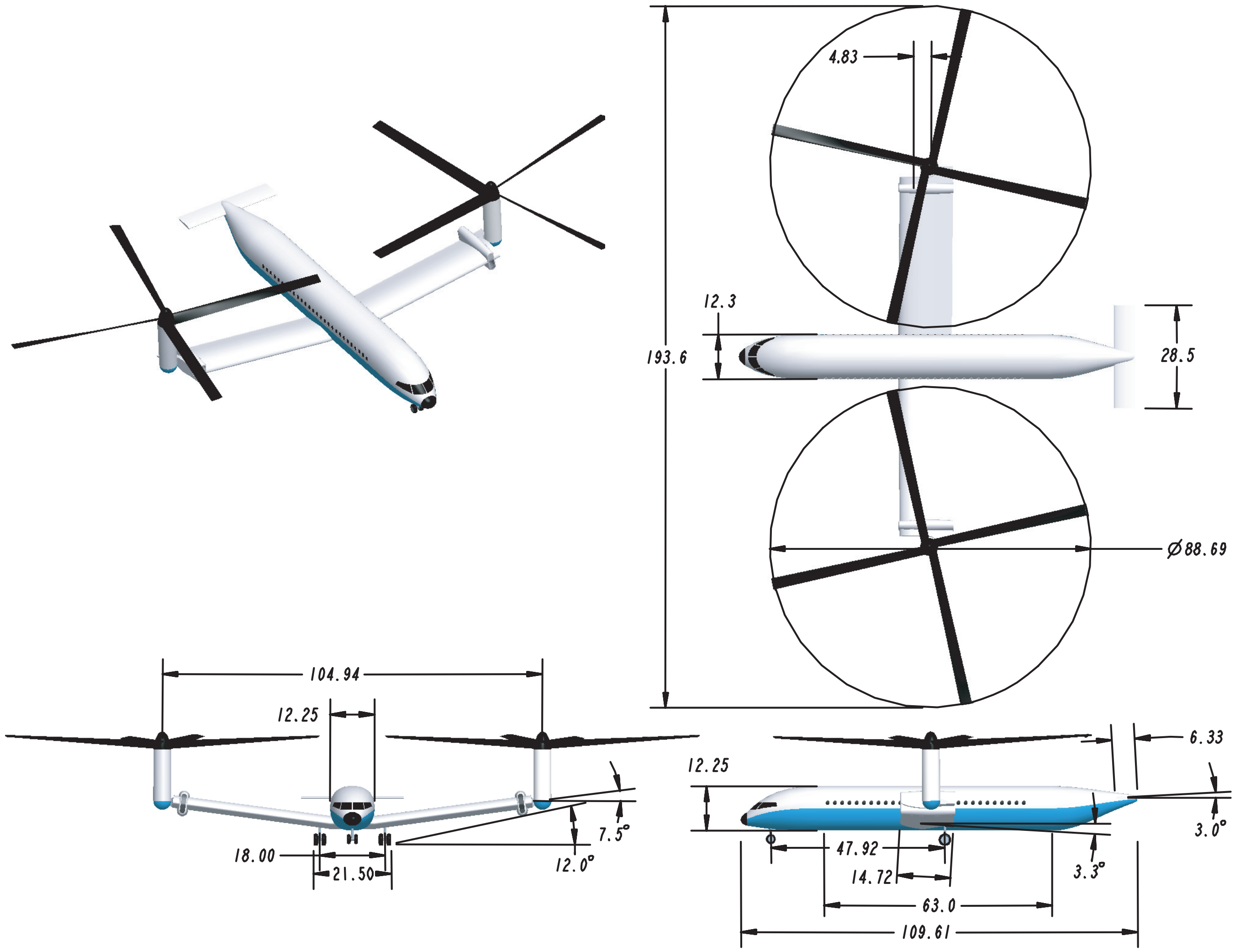


Fig. 1. LCTR concept design.

LCTR Conceptual Design

This report covers the Large Civil Tiltrotor (LCTR), illustrated in Fig. 1. Key design values are summarized in Table 1. It is designed for 350 knots at 30,000 ft altitude, with low disk loading in hover and low tip speed of 650 ft/sec in hover (for low noise) and 350 ft/sec in cruise (for high efficiency). Details are given in Ref. 1.

The objective of the LCTR design is to be competitive with regional jets and compatible with future, crowded airspace. The baseline civil mission is defined by NASA technology goals (Ref. 1) and is summarized in Table 2.

The rotorcraft design software RC performs the sizing of the rotorcraft, including mission performance analysis, and the comprehensive analysis CAMRAD II is used for rotor performance optimization and loads and stability calculations. RC was developed by the Aviation Advanced Design Office of the U. S. Army Aeroflightdynamics Directorate (AFDD), RDECOM (Ref. 3). CAMRAD II is an aeromechanical analysis for rotorcraft that incorporates a combination of advanced technologies, including multibody dynamics, nonlinear finite elements, and rotorcraft aerodynamics (Ref. 4). Other codes, such as NASTRAN and HeliFoil, are used for subsystem analyses. Reference 1 discusses the integration of the various design tools and methodologies into an global design process. For convenience, rotor and wing design are discussed in separate sections of this paper, below.

Performance requirements are derived from the NASA mission (Table 2) and are used by the RC sizing code to define the basic design; CAMRAD II then optimizes the rotor for performance. Rotor loads determine the rotor structural design. The wing structural design is derived from FAA certification requirements (Ref. 5). FAA requirements also set the aeroelastic stability boundary (whirl-flutter margin), which is checked for compliance by CAMRAD II. Aerodynamic optimization of the rotor is discussed in detail in Ref. 2 and is summarized here.

Table 1. Design values for LCTR.

Design Specification	Value
Cruise speed, knots	350
Cruise altitude, ft	30,000
Hover altitude, ft	5000
Tip speed, hover, ft/sec	650
Tip speed, cruise, ft/sec	350

Optimized Design	Result
Gross weight, lb	124,000
Rotor radius, ft	44.3
Number of blades	4
Rotor solidity	0.0881
Disk loading, lb/ft^2	10.0
Length, ft	110
Wing span, ft	105
Wing area, ft^2	1545
Wing loading, lb/ft^2	82
Drag D/q, ft^2	37.3
Engine power, hp	4×6914

Table 2. NASA civil heavy-lift mission.

Payload	120 passengers = 26,400 lb (with baggage)
Range	1200 nm
Cruise	Mach 0.6 at 30,000 ft (350 kts)
Hover at Denver	5000 ft ISA+20C (OEI at 22K ISA)
All weather operations	CATIIIC SNI
Community noise	SOA –14 EPNdb

Rotor Design Summary

A major motivation of the present research is the effect of very large size on rotor dynamics, i.e. scaling effects. Simply scaling up an existing rotor design to the size of the LCTR would result in unacceptable weight. However, for a given tip speed, a larger rotor will have a lower rotational speed. This allows blade frequencies to be lower in absolute terms (Hz) while remaining high in relative terms (per revolution). The prospect of a low-speed (rpm), high-blade-frequency (per rev) rotor opens the door towards much larger tiltrotors than current technology allows.

A hingeless rotor is the hub concept considered here, because of its simplicity and good stability. It is also compatible with a low-wing design. However, the high loads associated with such a design will require either an unusual blade design or active loads control. Note also the very low cruise tip speed for the LCTR design, which has important implications for loads and stability.

Details of the rotor design are given in Ref. 1 and are summarized here; Fig. 2 schematically illustrates the design procedure (a similar procedure for the wing design is discussed in the following section). Rotor tip speed (Table 1) is set by noise requirements in hover and efficiency requirements in cruise. The RC design code then determines the rotor radius and solidity required to meet the mission requirements in Table 2; the entire aircraft is sized simultaneously with the rotor. Rotor performance capability is derived from scaling rules and technology factors by RC. For example, drag is scaled from historical trends, with an additional factor representing new technology.

The notional rotor defined by RC is then aerodynamically optimized by CAMRAD II. Twist and taper are determined by selecting the optimum performance values from a large matrix of CAMRAD II analyses that cover both cruise and hover; the aerodynamic optimization procedure is covered in detail in Ref. 2. The blade load-carrying structure is generated by Pennsylvania State University (PSU), using in-house design software, to meet the loads calculated by CAMRAD II; see Ref. 6 for details of the blade structural design procedure. If needed, the rotor can be reoptimized without resizing the aircraft (inner loop of Fig. 2). To begin another design optimization cycle, RC is recalibrated to match the detailed CAMRAD II predictions for the current design. The aircraft and rotor are then re-sized and the components re-optimized.

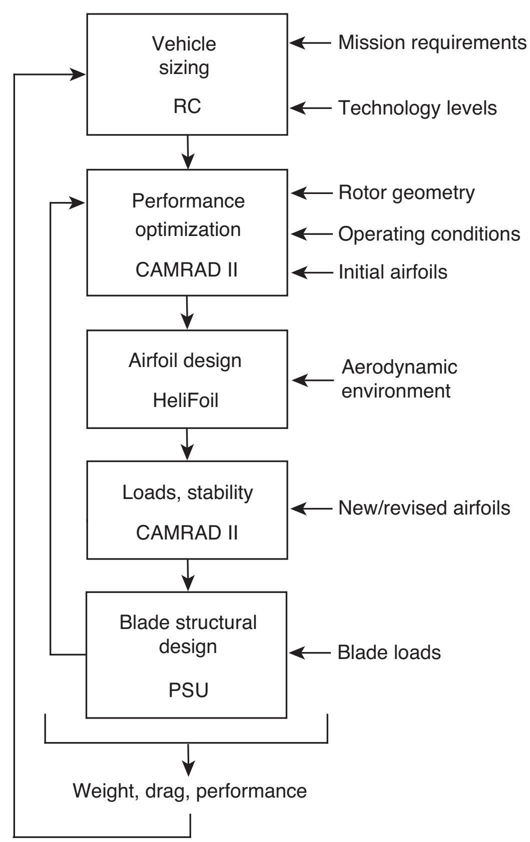


Fig. 2. Iterative rotor design process.

There is an option to add new, purpose-designed airfoils after initial optimization. The airfoil design was driven by the local flow conditions computed earlier in the optimization cycle. This typically required another cycle of rotor optimization (inner loop) to maximize the benefits of new airfoils (Ref. 2).

Figure 3 is an example result of the rotor optimization, here showing the performance boundary of a large matrix of rotor twist values for a given taper and identifying the twist values at several points on the boundary. Bi-linear twist was used, with one linear twist rate from the blade root to 50% radius, and a different linear twist from 50% radius to the tip. The calculations shown in Fig. 3 use a blade taper ratio (tip/root chord) of 0.8, and are trimmed to hover C_T/σ = 0.156 and cruise C_T/σ = 0.073. Current-technology airfoils (Ref. 7) are used here, but are limited to 18% maximum t/c.

The optimum value is at the peak propulsive efficiency of 0.814 because the mission is so heavily weighted toward cruise (Table 2); the corresponding figure of merit is 0.782. Isolated rotor performance in hover and cruise is calculated using a free wake model and is summarized in Figs. 4 and 5 for the optimized rotor (corresponding to the -32/-30 twist combination in Fig. 3).

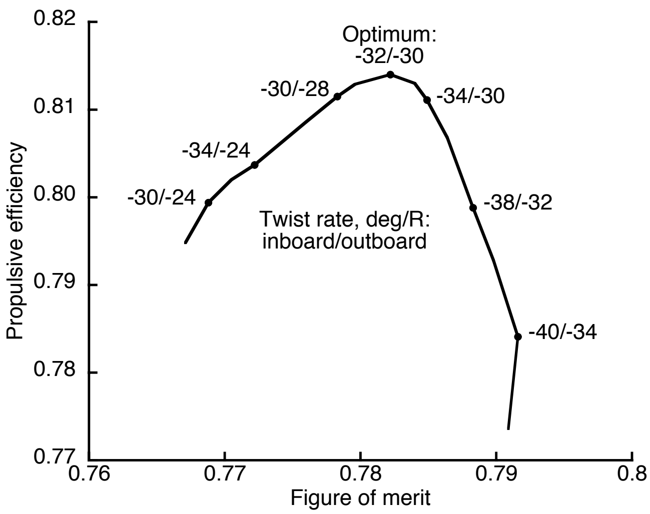


Fig. 3. Example rotor optimization: performance boundary for inboard/outboard twist variations.

Better performance is possible with purpose-designed airfoils, as discussed in Ref. 2. The design with current-technology airfoils is described exclusively herein because it was taken all the way through the iterative design process. The resulting performance, loads and stability calculations are, therefore, fully consistent.

The optimized rotor is examined for stability (flutter) in hover (Fig. 6). The analysis assumed an isolated rotor in axial flow, with no airframe or drive train modes. The rotor is stable until well into stall (C_T/σ > 0.22). The rotor is analyzed at fixed collective, so C_T/σ reverses trend after reaching its maximum value; stability declines rapidly thereafter. The flutter model is summarized in Table 3. All flutter calculations use a uniform-inflow, axial-flow aerodynamic model with a constant-coefficient flutter analysis.

Figure 7 shows the isolated rotor stability in cruise (axial flow, no airframe modes). The first flap-mode damping ratio reaches a peak value of 1.0 at the design cruise condition (well off the top of the scale of Fig. 7) and falls off rapidly near 475 knots, but all modes remain stable up to 500 knots.

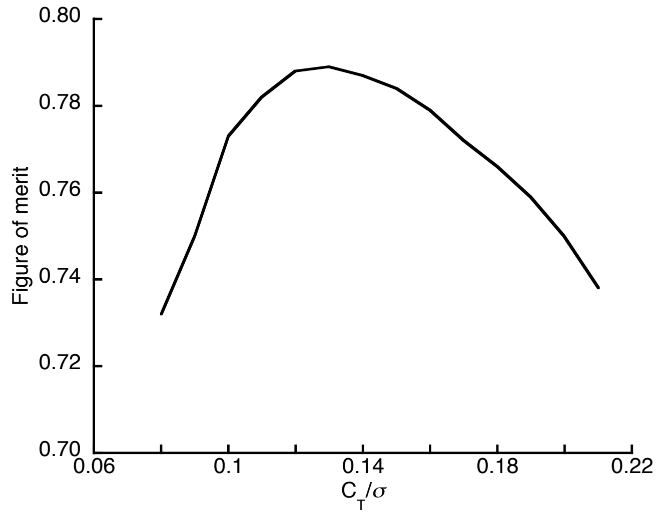


Fig. 4. LCTR hover performance (isolated rotor).

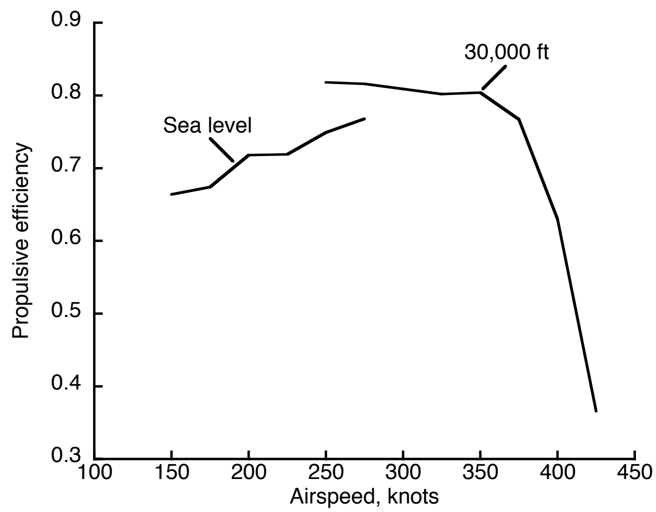


Fig. 5. LCTR cruise performance (isolated rotor).

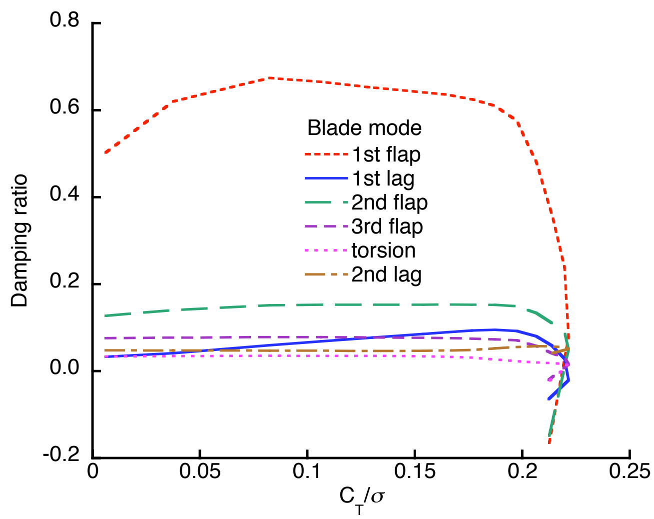


Fig. 6. LCTR isolated rotor stability in hover.

Table 3. CAMRAD II flutter model.

Hover Stability
10 blade modes
1% critical blade structural damping
no drive train
no aerodynamics (fixed collective trim)
Cruise Stability
6 blade modes
10 wing modes (Table 4)
rigid drive train (rotational inertia, but no shaft flexibility)
3% critical blade structural damping
3% critical wing structural damping
(no aerodynamic damping)
dynamic inflow
symmetric/antisymmetric analysis

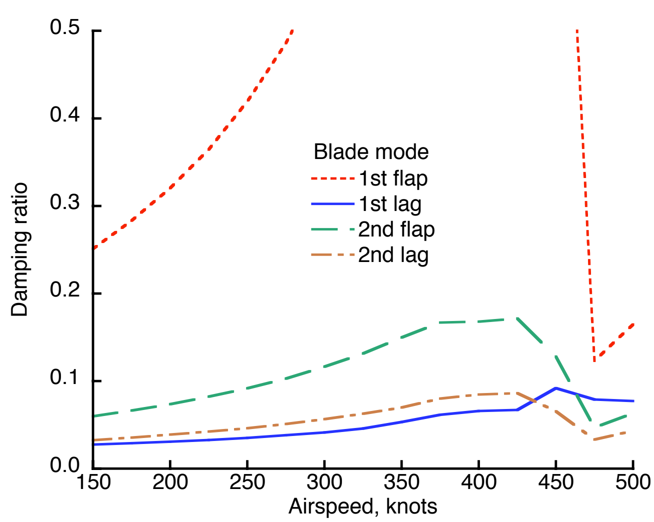


Fig. 7. LCTR isolated rotor stability in cruise.

LCTR Wing Design

The wing design process is summarized in Fig. 8. The airframe geometry and gross weight are determined by the RC sizing code; the rotor design is then optimized for performance with CAMRAD II. The RC wing weight estimate is based upon historical trends and scaling considerations (Ref. 3).

The basic wing structure is generated by Pennsylvania State University, based on loads requirements. The resulting wing structural parameters are fed into a NASTRAN model, which calculates wing mode shapes and frequencies. CAMRAD II then calculates the coupled rotor/wing stability. If needed for stability, the process is iterated by stiffening the wing. If the weight change imposed by either loads or stability is large enough to significantly change overall airframe weight, the RC sizing code is rerun.

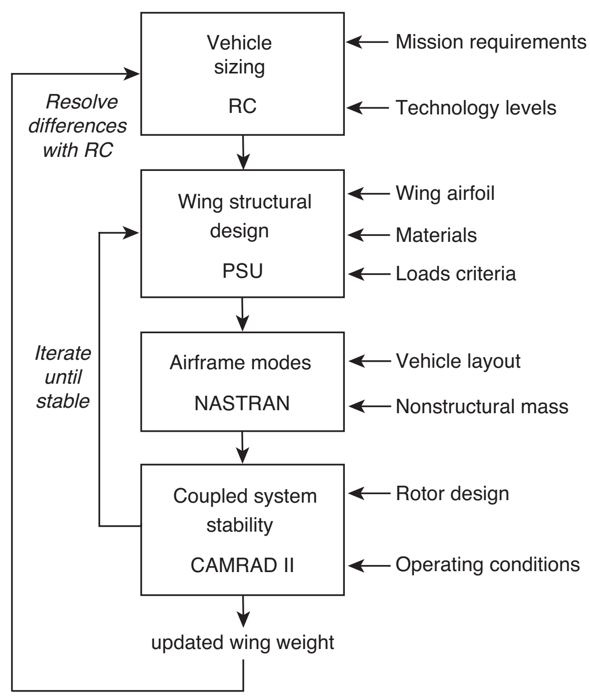


Fig. 8. Iterative tiltrotor wing design process.

Because whirl flutter and wing download present technology challenges for tiltrotors (and to a lesser extent, compound helicopters), the wing design requires careful attention. A tiltrotor wing must accommodate a transmission cross-shaft. For download reduction, the wing must also have full-span, large-chord flaps with very large deflections (up to 90 deg). The wing is tip-loaded in hover and low-speed maneuvers, and the concentrated tip masses (engines and transmissions) drive the wing structural dynamics. Moreover, large in-plane forces generated by the rotors at high-speeds can couple with the wing modes to cause whirl flutter. The wing might also accommodate emerging download-reduction technology (e.g. active aerodynamics).

Fixed-wing aircraft design practices are inappropriate to meet these collective requirements.

The large bending and torsional stiffnesses required for tiltrotor aeroelastic stability result in wings with unusually thick cross sections, compared with fixed-wing aircraft. Thinner wings have lower drag, but higher weight to carry the same loads. Purpose-designed airfoils are needed to simultaneously maximize aerodynamic and structural efficiency.

In contrast to current practice (e.g. V-22), the LCTR baseline design is a low-mounted wing (Fig. 1). The advantages over a high wing are a lighter, simpler structure to carry landing gear loads between fuselage and wing; no sponsons needed for landing gear, hence lower drag; and a potential reduction in download, resulting from elimination of the flow fountain over the fuselage (see Ref. 1). Design constraints include fixed engines with tilting shafts, longer rotor shafts or extreme dihedral for fuselage clearance in hover (for safety and low cabin noise), and hingeless rotors for adequate pitch control power in hover. (Cargo/military designs may retain a high wing to meet special requirements, e.g. folding.)

A serendipitous fallout of the low-wing configuration is that a hingeless rotor tends to be less susceptible to whirl flutter, so the wing need not be as torsionally stiff as would be required for a gimbaled or articulated rotor. However, a wing with a tilting shaft and fixed engines will have different maximum design loads (torsion component) than high-winged designs with tilting engines, because the offset between the rotor thrust vector and wing center of gravity will be different. Moreover, a hingeless rotor will require a load alleviation system. For these reasons, the wing and rotor cannot be designed independently of each other.

The LCTR wing structural design is driven by 2-g jump takeoff and VSTOL pullout loads, and by adequate stiffness to avoid whirl flutter. Table 4 summarizes the design requirements. Combined with low cruise rpm, the resulting lowest wing/nacelle frequency is greater than 2/rev. This is a very different design constraint than applies to any existing tiltrotor, so the wing structure cannot be extrapolated from current (V-22, BA-609) design practice.

Table 4. Wing design structural design requirements.

Purpose-designed wing airfoil (24% t/c), constant chord & section
Spar placement from AFDD designs (Ref. 8)
Design to 2-g jump takeoff loads (RC gross weight), plus 2-g symmetrical pullout with 75-deg pylons (scaled worst-case loads from Ref. 8)
Flutter margin 50% over cruise speed (Ref. 5)
IM7/8552 (graphite)
Tsai-Wu strength criteria, 1.5 factor of safety (Ref. 6)
Non-structural weight allowance for fuel tanks etc. (RC tech factors)

The wing structural design process is similar to that for the rotor blades (Ref. 6). The airfoil is designed to give the greatest possible thickness with acceptable drag at the specified cruise conditions (Table 1); the profile is shown in Fig. 9. The spar placement allows for large-chord flaps, a cross-shaft, and other non-load-carrying items. The material used is IM7/8552 (graphite), with the Tsai-Wu strength criteria and a 1.5 factor of safety.

The structural design criteria are a 2-g jump takeoff at the design gross weight (primarily for bending), and a 2-g symmetrical pullout with 75-deg nacelle angle (for torsion).

The initial section design was for minimum weight, with no requirements for flutter or frequency placement. No additional stiffening or other modifications were needed to meet the flutter margin; hence, the wing design was determined by loads requirements, not by stiffness. The resulting wing weight was 2000 lb lighter than the initial RC estimate.

Only the load-carrying structure (torque box) is designed here, because it dominates the final wing weight; RC applies additional, non-structural weights based upon the weight of the load-carrying structure. (No buckling criteria are applied at the conceptual design level, because that would require more design details than are available.)

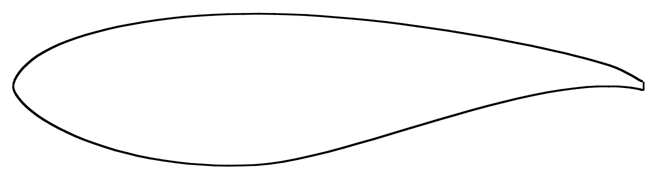


Fig. 9. 24% t/c wing airfoil; note truncated trailing edge.

The wing structural properties (inertia, stiffnesses, elastic axis, etc.) are incorporated into a NASTRAN finite element model of the airframe. A simple elastic-line model is used, derived from models developed by AFDD (Ref. 8). It includes the non-structural wing masses, rigid nacelles with rotor masses, and a flexible fuselage. The model comprises ten elastic wing spar elements and nine elastic fuselage elements; the layout is shown in Fig. 10. The fuselage elements model a simplified B-737, to represent worst-case weight and stiffness properties; a state-of-the art composite fuselage would be lighter and stiffer. A rigid, massless tail is included to help visualize the modes. The nacelle model is equivalent to the on-downstop configuration. Based upon this model, the resulting NASTRAN modes are used by CAMRAD II to calculate stability (whirl flutter).

Certain simplifications were applied to the NASTRAN model as appropriate for a conceptual design: there is no wing sweep, and the nacelle center of gravity is assumed to coincide with the wing elastic axis. The nacelle pitch inertia is scaled by RC based on technology factors; for this, there is no differentiation between fixed and tilting engine layouts.

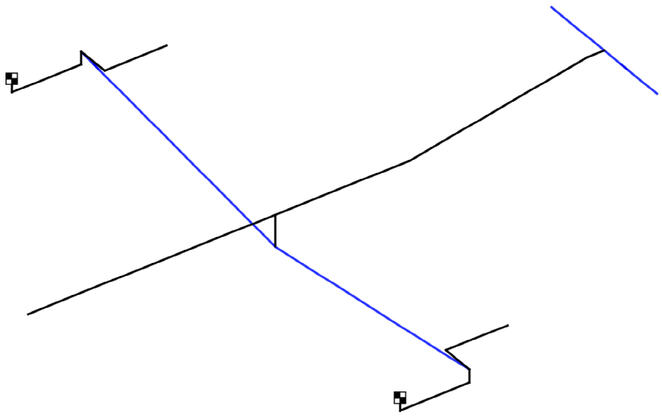


Fig. 10. NASTRAN elastic-line model.

The loads criteria of Table 4 are not definitive. They do not include chordwise loads resulting from yaw inputs in hover; such a loads specification will require development of handling qualities requirements beyond those of Ref. 1. Nor do they include provisions for concentrated landing gear loads. On the other hand, the scaled loads from Ref. 9 result in an over-designed wing, so further weight savings should be possible.

At this stage of the conceptual design process, the airframe structural dynamics model is necessarily very simple, but an elastic-line model (Fig. 10) is adequate to obtain the low frequency modes that are important for whirl flutter. The NASTRAN model is also needed for analysis of handling qualities, because low-frequency airframe modes can couple with flight control response.

The resulting modal frequencies are given in Table 5. Note that the frequencies tend to occur in closely spaced pairs, and all six wing frequencies lie within one Hz of each other. This makes conventional wing/rotor frequency placement (Ref. 9) impossible. The large transport fuselage with high pitch and yaw inertia and integral center wing structure results in symmetric/antisymmetric mode pairs with nearly the same frequencies (<0.05 Hz separation).

Whirl Flutter Analysis

CAMRAD II couples the airframe modes (external inputs) to rotor aeroelastic modes (internal calculations) to get a complete flutter solution. To get a conservative whirl-flutter boundary, the CAMRAD II model assumes structural damping of 3% critical for both the rotor and wing in cruise, but no wing aerodynamic damping (Table 3).

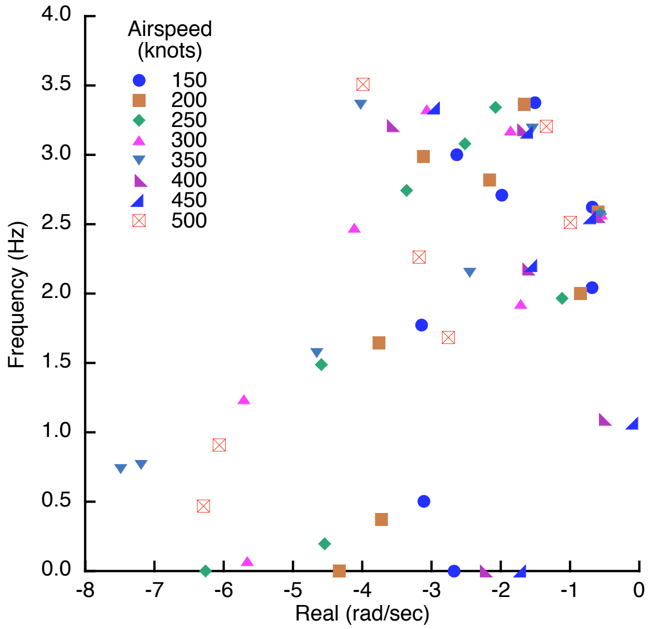
For cruise stability calculations, the rotor is trimmed to conditions known to simulate extremes of whirl flutter behavior: the rotor trimmed to zero power; or the rotor trimmed to thrust equal to aircraft drag up to the speed for maximum power, then trimmed to constant power at higher speeds (equivalent to a powered descent). Stability was calculated at both 30,000 ft and sea level (standard day).

With this CAMRAD II model for the airframe and the hingeless rotor, the LCTR meets the criterion for whirl flutter (Table 4). Hence loads, rather than whirl flutter, are the design drivers for both rotor and wing. Figure 11 shows example root-locus plots of coupled wing/rotor aeroelastic stability, with symmetric and antisymmetric modes plotted separately. All modes are stable, with no strong adverse trends.

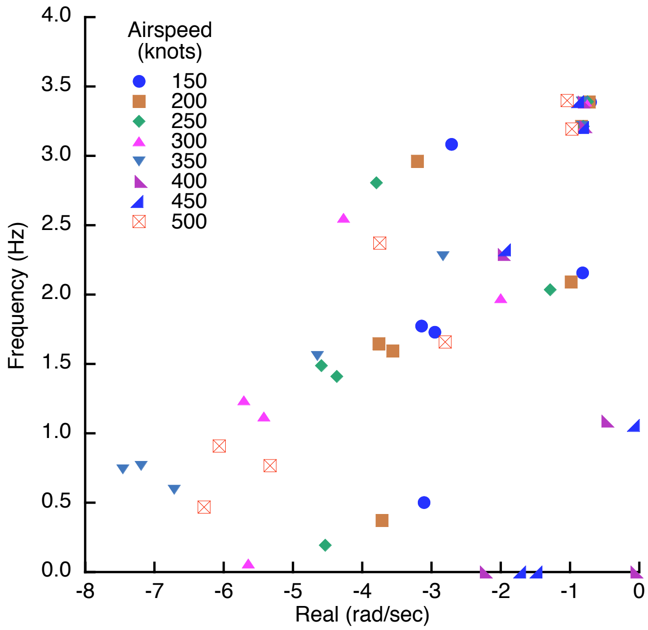
Figure 11 shows the worst-case flight condition for flutter: the zero-power cases (not shown) are slightly more stable than the maximum-power conditions. This is in contrast to past experience, probably because the low cruise rpm combined with low blade weight greatly reduces the adverse affects of mismatched precone (LCTR precone is 6 deg).

Table 5. NASTRAN modal frequencies for LCTR.

Symmetric Modes			Antisymmetric Modes		
Frequency		Mode	Frequency		Mode
Hz	Per rev		Hz	Per rev	
2.64	2.10	Wing beamwise bending	3.25	2.58	Wing beamwise bending
3.42	2.71	Wing torsion	3.47	2.75	Wing torsion
3.64	2.89	Wing chordwise bending	3.60	2.86	Wing chordwise bending
5.70	4.52	Vertical fuselage bending	5.64	4.48	Lateral fuselage bending
9.00	7.14	Aft fuselage bending	10.41	8.26	Lateral tail bending
Cruise 1/rev = 1.26 Hz (75.5 rpm)					



a) symmetric modes



b) antisymmetric modes

Fig. 11. Example aeroelastic stability (whirl flutter) predictions at 30,000 ft; trim to thrust until 350 knots, then trim to 350-kt power.

Future Efforts

Although the Heavy Lift Rotorcraft Systems Investigation is officially complete (Ref. 1), component and systems research continues. For the wing design presented here, the scaled torsion loads are over-specified, and the structural design does not take full advantage of taper; the wing is, therefore, almost certainly over-designed and overweight. More sophisticated loads criteria are being developed and applied to the wing design; in turn, the wing structural design is being refined. The objective is not just an improved wing design, but weight-scaling algorithms more appropriate for very large tiltrotors, which will enable the RC sizing code to produce more efficient designs at an earlier stage of the design iteration cycle.

The rotor design is being revised for lower cabin noise. This entails an additional design specification (minimum hover frequency) which will require a re-examination of disk loading, solidity and blade number. This can be expected to result in different whirl-flutter margins, although no difficulties are anticipated.

New rotor airfoils promise significant improvements in performance, but entail the risk of different transonic behavior and attendant changes in stability. Both isolated rotor and whirl-mode stability must be re-examined for any change in rotor airfoils.

Although the LCTR has no whirl-flutter issues, an advanced wing design could evolve into a low-drag, low-weight structure with inadequate torsional stiffness for stability. Therefore, flutter-alleviation measures should be considered as potential research areas. Demonstration of whirl-mode stability is required in any event. Stability-enhancement technology includes aeroelastic tailoring of the wing (bending/torsion coupling), active flutter suppression via high-frequency rotor control inputs, and possibly passive rotor design measures (aeroelastic tailoring, planform optimization, or mass distribution).

Conclusions

For very large tiltrotors, rotor and wing design are interrelated. A design method was developed that produces a low-drag, structurally efficient wing compatible with lightweight, aerodynamically efficient, stable rotors. A Large Civil Tiltrotor (LCTR) was designed to carry 120 passengers 1200 nm at 350 knots. This design employs a low-mounted wing and hingeless rotors, with very low cruise tip speed (V_{tip} = 350 ft/sec, 75.5 rpm). Optimization of the rotor with current-technology airfoils results in figure of merit of 0.782 and propulsive efficiency of 0.814 at design conditions.

The hingeless rotor, low-wing concept is stable: loads are the major design driver, not flutter. Full power is less stable than zero power, in contrast to conventional designs. Traditional frequency placement criteria are not appropriate for the wing design, and may be impossible: all wing frequencies are within 1 Hz (2.64-3.64 Hz), with the lowest wing/nacelle frequency above 2/rev.

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