Designs and Technology Requirements for Civil Heavy Lift Rotorcraft

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Abstract

The NASA Heavy Lift Rotorcraft Systems Investigation examined in depth several rotorcraft configurations for large civil transport, designed to meet the technology goals of the NASA Vehicle Systems Program. The investigation identified the Large Civil Tiltrotor as the configuration with the best potential to meet the technology goals. The design presented was economically competitive, with the potential for substantial impact on the air transportation system. The keys to achieving a competitive aircraft were low drag airframe and low disk loading rotors; structural weight reduction, for both airframe and rotors; drive system weight reduction; improved engine efficiency; low maintenance design; and manufacturing cost comparable to fixed-wing aircraft. Risk reduction plans were developed to provide the strategic direction to support a heavy-lift rotorcraft development. The following high risk areas were identified for heavy lift rotorcraft: high torque, light weight drive system; high performance, structurally efficient rotor/wing system; low noise aircraft; and super-integrated vehicle management system.

INTRODUCTION[·]

The Rotorcraft (RC) Sector was established in January 2004 as one of six vehicle sectors within the Vehicle Systems Program (VSP) of the NASA Aeronautics Research Mission Directorate. The principal aim of the RC Sector is to improve public mobility and access to air transportation. The technology goals of the Sector originated from industry studies and workshops during 2001-2004 that focused on a new class of vehicles known as Runway Independent Aircraft (RIA). References 1-2 showed that RIA can relieve runway and terminal area congestion by replacing small aircraft and short-haul flights that use primary runways. The primary runways would then be used exclusively for larger aircraft and medium/long-haul flights. RIA would operate from stub runways and/or helicopter landing pads. This operational concept would increase the capacity of the air transportation system. The increased capacity could then be used to increase throughput or reduce delay throughout the system. Reference 1 conservatively estimates 10.2% of flights in 2017 as candidates for RIA. By removing 10% of the flights from the primary runways, Ref. 1 projects 79% less delay in 2017, roughly equivalent to a cost avoidance of $181B per year. Alternatively, replacing the removed short-haul flights with medium- and long-haul flights would increase system capacity by 152 billion revenue passenger miles, which translates into added services to the public in addition to substantial revenue for the airlines. Reference 3 describes three RIA configurations analyzed by the rotorcraft industry: the quad tiltrotor (Bell Helicopter), the reverse velocity rotor concept (Sikorsky), and the tiltrotor (Boeing). The studies identified the benefits of advanced technology and the resulting effects on operating cost. In summary, Refs. 1-3 provide justification for the overwhelming positive impact that RIA can have on the national air space.

Using the RIA studies as motivation, the RC Sector is focusing on enabling technology for a notional civil VTOL transport capable of carrying 120 passengers at a cruise speed of 350 knots at 30,000 ft altitude with a range of 1200 nm (without refueling). This heavy-lift transport will be "neighborly" quiet when operating near communities, economically competitive with a Boeing 737 aircraft, and

[·]*Presented at the AHS Vertical Lift Aircraft Design Conference, San Francisco, California, January 18–20, 2006.*

will exploit available airspace and ground space (excluding primary runways). Specific 15-year technology goals for the notional transport are shown in Table 1. These extreme mission and technology goals were established by the RC Sector to push the state-of-the-art in rotorcraft technology. For comparison, the Mi-26, the largest helicopter in the world today, has a maximum speed of 160 knots with a service ceiling of approximately 15,000 ft and a range of 435 nm. The NASA Heavy Lift Rotorcraft Systems Investigation, the focus of this paper, is the first step toward attaining the RC Sector goals.

The objective of the investigation was to select a heavy lift rotorcraft system that has the best chance of meeting the goals of Table 1 while being economically competitive. The first four goals of Table 1 were given highest priority. The deliverables of the investigation were a candidate configuration for a large civil VTOL transport, and a description of the research and development required for risk reduction. A NASA-led team of rotorcraft technologists analyzed three notional vehicle configurations suggested by the rotorcraft industry: a tiltrotor, a tandem-rotor compound, and an advancing blade concept configuration. These configurations were deemed, as a first cut, to be technically promising. In contrast to the RIA configuration study of Ref. 3, the present investigation assesses all the candidate configurations against the same RC Sector mission and technology goals and provides detailed analysis in multiple technology areas. In approximately 12 months, the team performed extensive engineering analysis including aircraft design, performance optimization, blade and rotor aerodynamics, airframe aerodynamics, loads and stability analysis, blade structural design, external noise, one-engine inoperative requirements, handling qualities, and cost drivers. The team was divided into subgroups representing aeromechanics, acoustics, propulsion, structures, handling qualities, and cost. This approach was highly successful in attacking this complex design problem. Team members included Ames Research Center (primary responsibility for developing concepts), Glenn Research Center (engine and propulsion), and Langley Research Center (acoustics and structures). The Advanced Design Team of the U. S. Army Aeroflight-dynamics Directorate assisted with system design. The U. S. Army provided additional assistance in aeromechanics (RDECOM/ AFDD), engine and propulsion (ARL), structures and materials (ARL/VTD, AMCOM/ AATD). Contracts were established with Bell Helicopter, Boeing, and Sikorsky Aircraft to provide feedback on the NASA designs and risk reduction plans in addition to conducting limited sizing, design, and analysis of some of the concepts being investigated. Bell and Sikorsky prepared expositions on autorotation and one-engine-inoperative requirements for heavy lift. Also under contract were Pennsylvania State University (blade and wing structural design, airfoil design), and University of Maryland and Georgia Institute of Technology (assessments of slowed-rotor compound configurations, including reaction drive). An independent review group comprised of five non-government senior rotorcraft technologists with extensive design experience in the rotorcraft industry, U. S. Army, and academia provided feedback on the process and content of the investigation.

This paper presents the results of the NASA Heavy Lift Rotorcraft Systems Investigation. It describes the approach used for developing the designs for the tiltrotor, tandem-rotor compound, and the advancing blade concept configurations. Completed designs are presented together with trade studies to quantify the impact of technology and examine alternate missions. The configurations are then ranked in terms of ability to meet the RC Sector mission and goals. Finally, high risk areas for the selected configuration are identified and plans to mitigate the risks are presented.

DESIGN APPROACH AND ANALYSIS TOOLS

The approach taken was to design large VTOL transports that are economically competitive with today's regional jet airliners, and meet the RC Sector mission and goals. The principal cost drivers are weight and power. Advances in structural efficiency, aerodynamic efficiency, control concepts, propulsion concepts, dynamics solutions, and prediction capability should allow substantial reductions in empty weight, power, and fuel. Low power is ensured by low rotor disk loading and low aircraft drag. Light weight at large size requires advanced technology. The heavy lift rotorcraft designs required tasks covering aircraft design, performance optimization, aerodynamics analysis (airfoil, blade, airframe, rotor, aircraft), structural design (airframe, wing, blade), rotor loads and stability analysis, assessment of propulsion, noise, and handling qualities, one-engine inoperative review, and cost estimation. The intent of the investigation team was to perform these analysis tasks in as much detail and as much depth as possible during the 12-month period, in order to inform and support the recommendations for risk reduction activities.

The code RC performed the sizing of the rotorcraft, and the comprehensive analysis CAMRAD II was used for performance optimization, and loads and stability calculations. The sizing code incorporated significant weight savings (relative to current technology scaled to large size) as a result of structure, drive train, and engine technology. Cost models were developed, and used to estimate the purchase price and direct operating cost of the heavy lift rotorcraft designs. The sizing code was used to perform sensitivity analyses, first to optimize the aircraft (variations including disk loading, tip speed, and number of engines); and then to quantify the influence of advanced technology.

The code RC (Ref. 4) was the principal rotorcraft sizing and performance analysis tool for this investigation. RC was developed by the Advanced Design Team of the U. S. Army Aeroflightdynamics Directorate, RDECOM. Designer inputs to RC include design strategy (engine sizing, rotor sizing, etc.), rotorcraft parameters (drag coefficients, tail volume ratio, etc.), and requirements and constraints (take-off, payload, range, etc.). RC finds the aircraft that satisfies the designer inputs, then produces the rotorcraft description, and conducts the performance analysis.

Technology in the sizing code is introduced in terms of technology factors and performance models. Weights (at the group weight level of detail) are estimated from statistical equations. These equations are calibrated to current technology level by comparing with existing aircraft. Technology factors are then applied to represent the impact of advanced technology. In this approach, technology is a change from the statistical equation, attributed to a new configuration or concept, new materials, new design methods, new operating procedures, etc. There are technology factors for blade and hub weight, vibration treatment, drive system weight, and fuselage, wing, and tail weight. Technology also influences performance, in particular rotor hover and cruise efficiency, hub drag, and the engine weight and performance.

CAMRAD II is an aeromechanical analysis of helicopters and rotorcraft that incorporates a combination of advanced technologies, including multibody dynamics, nonlinear finite elements, and rotorcraft aerodynamics (Ref. 5). The trim task finds the equilibrium solution (constant or periodic) for a steady state operating condition, and produces the solution for performance, loads, and vibration. The flutter task linearizes the equations about the trim solution, and produces the stability results. The aerodynamic model includes a wake analysis to calculate the rotor nonuniform induced-velocities, using rigid, prescribed or free wake geometry. CAMRAD II has undergone extensive correlation with performance and loads measurements on helicopters, tiltrotors, and other rotorcraft configurations. Complete aeroelastic models were developed for each of the configurations considered in this investigation.

An assessment of engine and drive train technology was made in order to define and substantiate the sizing code models. The engine model represented what could be obtained from (or required of) modern technology engines. Drive train concepts were developed for the heavy lift rotorcraft designs.

Blade structural loads calculations were used to design rotor blade sections; and the resulting blade structural and inertial properties were used to repeat the loads calculations. This structural design required an assessment of advanced materials and application of innovative design and optimization techniques, in order to achieve a low weight at large size. A similar approach was used for the structural design of the wing sections. The resulting wing structural and inertial properties were used to develop NASTRAN finite element models of the airframe. The NASTRAN modes were used in CAMRAD II to calculate stability (particularly tiltrotor whirl flutter), linearized matrices for handling qualities analysis, and vibration.

The handling qualities of the aircraft were assessed, and the results used to guide the choice of configuration parameters for the sizing code. Expositions on autorotation and one-engine inoperative requirements for heavy lift rotorcraft were developed independently by Bell Helicopter and Sikorsky Aircraft, considering requirements and design implications. One-engine inoperative requirements were defined for use in the sizing code.

The rotor performance model in the RC sizing code was calibrated using the performance calculated by CAMRAD II, and the sizing task repeated. An estimate of the drag of the airframe was used to define the aerodynamic model for the sizing code and the comprehensive analysis. Based on aerodynamic environment calculations from CAMRAD II, rotor blade airfoils were designed using the code MSES (Ref. 6). Airfoil decks were constructed for the new airfoils, and used in the performance calculations. The contours of these airfoils were used in the blade structural design. A similar approach was used for aerodynamic design of wing airfoils. The three-dimensional Navier-Stokes analysis OVERFLOW-D was used to calculate the flow about the tiltrotor proprotor and pylon/nacelle. In addition, low fidelity CFD calculations using the Rot3DC code (Ref. 7) were performed of the entire tiltrotor flow field, including cruise drag and hover download calculations.

Making use of the comprehensive analysis model, the aircraft noise was assessed using the CARMA system (Ref. 8), and the results used to guide the choice of configuration parameters for the sizing code. An assessment was made of the relative contributions of aircraft configuration parameters, rotor active control, and flight procedures towards the acoustics goals.

The result of this process was three heavy lift rotorcraft designs supported by substantial in-depth engineering analyses, and guidance and focus for the development of the risk reduction plans.

COST MODELS

Cost models were developed for VTOL and CTOL aircraft, based on statistical information for current operations. The cost metrics considered were flyaway cost (purchase price, in 2005 US dollars) and direct operating cost plus interest, DOC+I (in 2005 US cents/ASM). The components of DOC+I were maintenance (airframe, engine, rotor and drive), flight crew, fuel and oil, depreciation, insurance, and finance cost.

A principal source for the cost models was Ref. 9 and its unpublished extensions. The parametric estimate of flyaway cost was based on data for 120 helicopters and 2 tiltrotors, with the U. S. multi-engine turbine helicopters covering a weight range from the Bell 206L to the CH-53E. The parametric equation gave flyaway cost from empty weight and installed power ($/lb nearly just a function of W_E/P), and the number of rotors and number of blades. The parametric estimate of maintenance cost was based on civil operations; the result was a function of weight empty and installed power. Flight crew costs were proportional to block hours. Depreciation, insurance, and finance cost were all proportional to flyaway cost.

The CTOL cost model was based on the economics of U. S. airline operations.

In order to compare VTOL and CTOL costs, the two cost models were applied to a Boeing 737-700 at a stage length of 500 miles. For the 737 in the VTOL cost model, the minimum complexity was used (one rotor and one blade), and an installed power trend was used to get an equivalent turboshaft power. The costs are substantially higher with the VTOL model. With these results it is possible to establish cost technology factors:

Maintenance tech factor = 0.9/9.8 = 0.092
Flyaway price tech factor = 48.0/83.6 = 0.57

Insurance, depreciation, and finance costs are driven by flyaway price. Baseline cost estimates for the heavy lift rotorcraft designs were obtained using the above cost technology factors. A significant part of the differences between VTOL and CTOL costs must be the very different operations that produced the cost data used to develop the models. The remaining differences in cost must be attacked by advanced technology. Note in particular the importance of maintenance costs.

For the same mission, a VTOL aircraft will have higher gross weight and higher installed power than a CTOL aircraft. In addition, there are complexity factors in the VTOL model, including number of rotors and number of blades. Thus there is still a cost of VTOL capability in the cost model, even when the maintenance and flyaway price technology factors are used.

CONFIGURATIONS

Three aircraft configurations were the primary subject of the Heavy Lift Rotorcraft Systems Investigation:

1) Large Civil Tiltrotor (LCTR)
2) Large Civil Tandem Compound (LCTC)
3) Large Advancing Blade Concept (LABC)

These configurations were selected by industry as the most promising candidates for the civil mission. The conventional two-rotor tiltrotor configuration was considered, since a quad tiltrotor would not present as much of a challenge in terms of rotor size. A low rotor speed was used for the tiltrotor in cruise, to improve the proprotor propulsive efficiency. The LCTC and LABC use edgewise rotors in cruise, hence the rotor rotation must be slowed as the flight speed increases, to keep the advancing tip Mach number reasonable. The LCTC is a slowed-rotor compound: it has a wing and auxiliary propulsion for cruise, so the rotors are operated in an unloaded condition. The LABC uses stiff coaxial main rotors capable of carrying significant roll moment, hence generating lift on the rotor advancing side in forward flight. The LABC requires auxiliary propulsion at high speeds, but has no wing.

The slowed-rotor compound considered had shaft-driven tandem main rotors. Single main rotor and coaxial main rotors are alternate configurations. The number and arrangement of the main rotors affects performance through rotor/rotor and rotor/wing interference; and affects the aircraft size because of antitorque and transmission layout issues. An alternative to shaft drive is a reaction drive configuration, typically using jets at the blade tips. The reaction drive is used in hover; in cruise the rotor is operated in autorotation. With reaction drive the transmission weight is greatly reduced, but the rotor cruise performance is compromised by the need for thick blades, and the hover performance is poor because of high energy losses entailed in delivering the air to the blade tips.

A major objective of the Rotorcraft Sector programs is to examine the potential of active control as enabling technology for heavy lift, based on weight reduction and/or solution of dynamic or aerodynamic problems. In particular, attention is being given to on-blade control, including trailing edge flaps, leading edge droop, active twist, and active flow control. The present investigations contributed to identifying what problems (loads, vibration, stability, noise, gust response, etc.) must be attacked using active control.

MISSION AND DESIGN CONDITIONS

Based on the Rotorcraft Sector notional vehicle capabilities and technology goals, a civil mission was defined. This investigation is not intended to specify the market, but rather to identify enabling technology for civil applications of heavy lift rotorcraft. Table 2 describes the mission, and Table 3 describes the payload and fuselage. Note in particular the OEI requirement in Table 2: at takeoff conditions (5k ISA+20^{o}C) the contingency power of the remaining engines (133% OEI MCP) must be greater than 90% hover out-of-ground-effect power required (the factor of 90% accounting non-zero speed and some altitude loss during the takeoff).

For maximum utilization, the aircraft must have a wide range of capabilities. Although the aircraft were designed to the mission defined in Table 2, hence with very little hover time, efficient hover and low speed capability is essential to the RIA operational concept. This is reflected in the requirement for essentially OEI hover capability. The resulting designs optimize at balanced cruise and OEI hover power, so the cruise speed of 350 knots can be viewed as a fallout of the OEI requirement. Reasonable downwash and outwash from the rotors hovering in ground effect is required for effective utilization. For example, a downwash of 20 lb/ft^2 would produce an outwash with a peak velocity of over 90 knots. As a result of these considerations, high disk loading aircraft (such as tiltwings) were not among the configurations considered here.

Critical design conditions appropriate for civil heavy lift rotorcraft operations were defined for calculation of performance, loads, and stability. Table 4 summarizes these aeromechanics analysis conditions.

TECHNOLOGY FACTORS AND DESIGN PARAMETERS

Meeting the technology goals of the NASA Rotorcraft Sector requires high speed, high altitude, and long range for productivity. The heavy lift rotorcraft must have low disk loading for good hover efficiency, and low drag for efficient cruise. The target for improvement in hover efficiency implies a disk loading on the order of W/A = 10 lb/ft^2. The actual disk loadings of the designs were determined based on minimum aircraft weight, power, and cost. For this heavy lift rotorcraft investigation, the target airframe and wing drag was $D/q = 1.6(W/1000)^{2/3}$. This drag level is higher than current turboprop aircraft, although about 35% lower than is customary in the helicopter industry. So good aerodynamic design practice should be sufficient to achieve the target for airframe drag. For concepts with edgewise rotors in cruise, hub drag must be added to the airframe and wing drag of the aircraft. For this investigation, the target hub drag was $D/q = 0.4(W/1000)^{2/3}$, which is less than half of current hub drag levels. Achieving this hub drag level will require advanced technology, certainly fairings but possibly also active flow control.

The weight technology factors used for the three baseline rotorcraft designs are summarized in Table 5. In the RC weight equations, the blade and hub weight technology were actually characterized by the blade flap frequency; the equivalent multiplicative factors are given in Table 5. The baseline technology for the present designs was hingeless rotors. Advanced technology rotors have light blades, hence the actual blade flap frequencies are high. Weight reduction obtained from technology was specified by a reduced equivalent flap frequency in the weight equations, reflecting new design concepts for the blades and hub. In these terms, the flap frequency was reduced by the factor 0.91 relative current technology, resulting in the multiplicative factors given in Table 5. In addition, the weight equations used had a factor of 1.18 for tiltrotor blades compared to helicopter blades, based on calibration with current technology. The drive system weights for the baseline aircraft were calculated using the technology factor given in Table 5, without any penalty for using a two-speed transmission design.

A scaled engine model was used by the sizing code. The current and advanced engine technology is characterized in Table 6. This model and technology were defined for engines with SLS MCP greater than 5000 hp.

The definition of the technology level in the sizing code also involves performance and aerodynamics. For the rotor, the design blade loading C_W/σ was prescribed, based on an assessment of what advanced technology could provide. Rotor induced and profile power in the sizing code were calibrated to the results of the comprehensive analysis calculations. Thus the sizing code performance represented a rotor with optimum twist, taper, cruise tip speed, etc. However, current technology airfoils were used in the comprehensive analysis optimization. Some further improvement in aircraft performance can thus be expected from the use of advanced technology airfoils, especially if specifically designed for these aircraft. Airframe drag was specified as described above. Current technology values were used for hover download. Some further improvement in aircraft performance might be obtained from download reduction.

The statistical weight equations used in the design code incorporate an influence of aircraft size, based on historical trends. For rotorcraft designed to fixed disk loading, tip speed, blade loading (solidity), and number of blades, these equations imply that rotor blade, rotor hub, and drive system weight scale with gross weight to the 1.26, 1.39, and 1.12 power, respectively. So for an increase in gross weight by a factor of 2.0, the rotor blade, rotor hub, and drive system weight increase by factors of 2.4, 2.6, and 2.2; and the aircraft structural and drive system weight therefore increases by about a factor of 2.2. In order to maintain aircraft empty weight fraction as size increases, the design approach must be changed, which conventionally has resulted in an increase in disk loading with size.

Basic parameters of the rotorcraft were chosen for the three heavy lift configurations based on an assessment of current and future technology (Table 7). The rotor blade loading (C_W/σ, based on gross weight and thrust-weighted solidity) was chosen considering low speed maneuverability requirements. The C_W/σ values in Table 7 correspond to about an 8% improvement in maximum lift capability, compared to current technology. A relatively low hover tip speed was used, reflecting the importance of the noise goal. The cruise tip speed was chosen to optimize the performance. To be conservative, hover download values consistent with current technology were used. A low wing loading was chosen, for good low speed maneuverability and wide conversion speed range. The same blade loading and wing loading design values were used for both tiltrotor and slowed-rotor compound configurations.

SUMMARY OF DESIGNS

The heavy lift rotorcraft designs are summarized in Table 8. Three-views of the aircraft are shown in Figures 1–3. Recall that for these designs the blade loading, hover tip speed, and wing loading were specified, based on assessments of the technology. Cruise tip speed was optimized based on cruise efficiency. The disk loading was optimized, based on aircraft weight, power, and cost. Basically the optimum disk loading produces a balance in power requirement between cruise and OEI hover. Cruise efficiency defines the power available, then the disk loading is chosen that uses that power in hover (a larger rotor would increase the rotor and blade weight, while a smaller rotor would require more power hence more engine and fuel weight). Table 9 compares the component weights of the three designs. The empty weight fraction is about 65%. The fixed weight is comparable to current commercial jet aircraft. Table 10 shows the cruise drag buildup. The drag of the LCTR is comparable to good turboprop aerodynamic design. The LCTC adds the drag of the hub (less than current technology levels), and the LABC does not have the drag of the wing. This LABC design was produced by the sizing code using a rotor cruise L/D_e that was higher than that predicted by the comprehensive analysis.

The aircraft cruise L/D=WV/P (based on cruise power, including losses, at design gross weight) was the principal efficiency metric. For the mission considered, the LCTR had the best cruise efficiency, hence the smallest design gross weight and the smallest installed power (Table 8). Next in efficiency is the LCTC, and after that the LABC.

Figure 4 shows the flyaway cost and DOC+I for the three heavy lift rotorcraft configurations, and Figure 5 presents the DOC+I breakdown for the 1200 nm design mission. These figures include the Boeing 737 costs for comparison. The block hours per year value was based on Southwest Airlines operations. The difference in dead time between the VTOL and 737 reflected the difference in operations. For the VTOL costs, the aircraft parameters (empty weight, installed power, number of rotors and number of blades) and the mission parameters (fuel weight, block time and block speed for a specified range) were obtained from the RC code.

The VTOL cost model is driven by gross weight and power, so the LCTR has the lowest cost, followed by the LCTC and then the LABC. At the design stage length, the LCTR cost is about 20% higher than that of a current 737. That is the cost of VTOL capability. The LCTR is more economical than the 737 for stage lengths below about 200 miles.

LARGE CIVIL TILTROTOR (LCTR)

The configuration of the Large Civil Tilt Rotor (LCTR) is shown in Figure 1. The aircraft had two tilting rotors at the wing tips, a low wing, non-tilting engines, and a horizontal tail. A quad tiltrotor (two wings and four rotors) would have smaller rotors, but increased complexity and increased aerodynamic interference. The conventional two-rotor tiltrotor configuration was considered here, which allowed more exploration of the implications of large size on the rotor system design. A low wing was adapted for better structural load paths between wing, airframe, and landing gear. The horizontal tail was sized by trim requirements rather than stability, because the rotors can be used for flight dynamics stabilization as well as control. A vertical tail is not shown, but could be added if needed for yaw trim.

Table 11 gives the aircraft characteristics. Performance, loads, and stability calculations were performed for the conditions defined in Table 4. For helicopter mode loads calculations, lateral flapping was trimmed to zero using lateral cyclic. Symmetric trim was used for cruise performance and helicopter mode loads calculations (trim aircraft lift, drag, and pitching moment). For cruise stability calculations, the rotor was trimmed to conditions known to simulate extremes of whirl flutter behavior: the rotor trimmed to zero power; or the rotor trimmed for aircraft drag equilibrium up to maximum power, and then trimmed to constant power.

A hingeless rotor hub was used. To reduce mean blade bending loads, the hub incorporated 6 deg precone and 0.002R torque offset. For blade stability, the chordwise center of gravity offset was constrained to be no farther than 5% chord aft of the quarter chord. Excessive coning can significantly reduce hover figure of merit. So a tip mass of 1.5 slug was placed on each blade at 95%R, in order to reduce coning and thereby improve hover performance (an increase in hover figure of merit of about 2% was produced). Figure 6 shows the calculated blade frequencies, at collective pitch angles representative of helicopter mode and cruise. At helicopter mode tip speeds, the lag frequency was above 2/rev and the torsion frequency above 12/rev. With these dynamic characteristics, no stability issues were observed, either blade or whirl flutter.

The blade twist and taper were varied to optimize the rotor for hover and cruise performance. The hover condition was 5k ISA+20°C, 650 ft/sec tip speed, C_T/σ = 0.1557. The cruise condition was 350 knots, 30k ISA, 350 ft/sec tip speed, trim aircraft drag. The twist distribution had two linear segments, inboard (0.0R to 0.5R) and outboard (0.5R to 1.0R). The comprehensive analysis did not have a collocation point at 0.5R, so a transition from inboard slope to outboard slope was not modelled. The taper model considered was constant thrust-weighted solidity (constant 75%R chord). Figure 7 presents the results for twist optimization, showing the typical hover-cruise compromise. The result was an optimum twist of –32 deg inboard and –30 deg outboard; and an optimum taper of 0.8 (tip/root chord).

The rotor performance from the sizing code and the comprehensive analysis are compared in Table 12. The RC model was adjusted to match the CAMRAD II performance at the design conditions. These results are for current technology rotor airfoils. Figures 8 and 9 show the hover and cruise performance of the main rotor.

LARGE CIVIL TANDEM COMPOUND (LCTC)

The configuration of the Large Civil Tandem Compound (LCTC) is shown in Figure 2. The aircraft had two main rotors in tandem configuration, a high wing, pusher propellers for cruise propulsion, and a horizontal tail. The length of the fuselage follows from the specification of the payload, and the disk loading was optimized to balance the cruise and hover power. As a result there was no overlap of the rotors. The horizontal tail was sized by trim requirements rather than stability.

Table 11 gives the aircraft characteristics. Performance, loads, and stability calculations were performed for the conditions defined in Table 4. The comprehensive analysis modelled the auxiliary propulsion as forces applied to the airframe. Rotor/rotor and rotor/wing interference were accounted for using the vortex wake model.

In hover and low speed flight, standard tandem helicopter controls, plus aircraft pitch and roll attitude, could be used to trim this aircraft. At moderate speeds, the pitch angle could be fixed and the propeller thrust trimmed instead. Even at low speeds, the lateral stick would be connected to the ailerons, and the longitudinal stick to the elevator. For the 80 knot load factor sweep (to obtain blade loads), the mean propeller thrust was fixed at the aircraft drag value, and the pilot's controls plus aircraft pitch and roll attitude were used to trim the aircraft (with pilot's collective, longitudinal cyclic, lateral cyclic, and pedal connected to mean rotor collective, differential collective, ailerons, and differential propeller thrust respectively). In addition, flapping was trimmed to zero (for load control) using rotor cyclic pitch; thus there were 10 trim variables for the load factor sweep.

In cruise the aircraft was trimmed using lateral stick to the ailerons, longitudinal stick to the elevator, pedal to differential propeller thrust; plus propeller thrust, and aircraft pitch and roll angles. Front and rear rotor collective pitch angles were set to values optimized for cruise performance (optimized rotor thrust). In addition, rotor flapping was trimmed to zero (for load control) using rotor longitudinal and lateral cyclic; thus there were 10 trim variables for cruise.

A hingeless rotor hub was used. Figure 10 shows the calculated blade frequencies, at a collective pitch angle of 10 deg. At helicopter mode tip speeds, the lag frequency was above 6/rev and the torsion frequency about 7.5/rev.

With these dynamic characteristics, no stability issues were observed, either in hover or in high advance ratio forward flight.

The blade twist and taper were varied to optimize the rotor for hover and cruise performance. The hover condition was 5k ISA+20°C, 650 ft/sec tip speed, C_T/σ = 0.1491. The cruise condition was 350 knots, 30k ISA, 205 ft/sec tip speed, 138764 lb gross weight. The twist distribution had two linear segments, inboard (0.0R to 0.5R) and outboard (0.5R to 1.0R). The taper model considered was constant thrust-weighted solidity (constant 75%R chord). Figure 11 presents the results for twist optimization, showing the hover-cruise compromise. For each value of outboard twist, the inboard twist values are 3, 0, –3, and –6 deg. The result was an optimum twist of 0 deg inboard and –12 deg outboard; and an optimum taper of 0.8 (tip/root chord).

Collective pitch of the front and rear rotors was varied to find the optimum rotor thrust for high speed cruise flight. For an untwisted rotor, the best aircraft performance would be obtained with zero collective (no lift, no induced power, minimum profile power). With negative outboard twist, for improved hover performance, the optimum collective was –2 deg, which resulted in the rotors carrying about 10% of the aircraft lift (the rotor thrust variation with collective was negative at this high advance ratio). This optimum occurred with a small, positive shaft power to the rotors. With the rotor in autorotation (achieved using an aft tilt of the rotor) the rotor thrust was large, hence the total rotor drag larger and the aircraft L/D somewhat smaller.

The rotor advancing tip Mach number was varied, and the optimum cruise performance was found at M_{at} = 0.80 (for the airfoils used). Further reductions in rotor rotational speed did not improve the aircraft L/D.

The rotor performance from the sizing code and the comprehensive analysis are compared in Table 12. The RC model was adjusted to match the CAMRAD II performance at the design conditions. These results are for current technology rotor airfoils. Figures 12 and 13 show respectively the hover performance of the main rotor and the aircraft cruise performance. The rotor performance in cruise is presented in terms of aircraft L/D=WV/P, calculated without accessory or other losses, and using a propeller efficiency of 0.86 (from the sizing code).

LARGE ADVANCING BLADE CONCEPT (LABC)

The configuration of the Large Advancing Blade Concept (LABC) is shown in Figure 3. The aircraft had two main rotors in coaxial configuration, pusher propellers for cruise propulsion, and horizontal and vertical tails for cruise trim. Ducted propellers on stub wings might be a better configuration for the auxiliary propulsion.

Table 11 gives the aircraft characteristics. Performance, loads, and stability calculations were performed for the conditions defined in Table 4. The comprehensive analysis modelled the auxiliary propulsion as forces applied to the airframe. Rotor/rotor interference was accounted for using the vortex wake model.

In hover and low speed flight, standard coaxial helicopter controls, plus aircraft pitch and roll attitude, were used to trim the aircraft. At moderate speeds, the pitch angle was fixed and the propeller thrust trimmed instead. Even at low speeds, the pedal was connected to the rudder, and the longitudinal stick to the elevator. In addition, differential hub moment was trimmed to zero (for load control) using differential cyclic; thus there were 8 trim variables for low speed flight.

In cruise the aircraft was trimmed using lateral stick to rotor lateral cyclic, longitudinal stick to the elevator, pedal to the rudder; plus propeller thrust, and aircraft pitch and roll angles. Lift offset (rotor differential roll moment) was trimmed to a specified value using differential lateral cyclic. Rotor collective pitch angles were set to values optimized for cruise performance (optimized rotor angle of attack). In addition, rotor pitch moment was trimmed to zero (for load control) using rotor longitudinal cyclic; thus there were 9 trim variables for cruise.

A hingeless rotor hub was used. Figure 14 shows the calculated blade frequencies, at collective pitch angle of 0 deg. At helicopter mode tip speeds, the flap frequency was about 3/rev, the lag frequency about 9/rev, and the torsion frequency above 15/rev. With these dynamic characteristics, no stability issues were observed, either in hover or in high advance ratio forward flight.

The blade twist and taper were varied to optimize the rotor for hover and cruise performance. The hover condition was 5k ISA+20°C, 650 ft/sec tip speed, 160636 lb gross weight. The cruise condition was 350 knots, 30k ISA, 255 ft/sec tip speed, 160636 lb gross weight. The twist distribution had two linear segments, inboard (0.0R to 0.5R) and outboard (0.5R to 1.0R). The result was an optimum twist (equivalent twist rate from root to tip) of 2 deg inboard and –12 deg outboard. The chord distribution also consisted of two segments with linear variation, inboard and outboard of 0.5R. The result was an optimum taper ratio (equivalent tip chord to root chord ratio) of 2 inboard and 1/3 outboard.

Collective pitch of the rotors was varied to find the optimum rotor shaft angle for high speed cruise flight. With the twist used, the optimum collective was 0 deg.

Rotor lift offset (differential roll moment) was varied, and the best cruise performance found for 0.2R offset (differential roll moment divided by gross weight and rotor radius). The rotor advancing tip Mach number was varied. The optimum cruise performance was found at M_{at} = 0.85 (for the airfoils used).

The rotor performance from the sizing code and the comprehensive analysis are compared in Table 14. Figures 15 and 16 show respectively the hover performance of the main rotor and the aircraft cruise performance. These results are for current technology rotor airfoils. Figure 16 also shows the cruise performance that might be achieved using advanced airfoils, here simulated by assuming a 10% reduction in drag and a 10% increase in critical Mach number relative the current technology airfoils (which optimizes to the same twist and taper as with current technology airfoils, but at a lift offset of 0.2%R and M_{at} = 0.90). The rotor performance in cruise is presented in terms of aircraft L/D = WV/P, calculated without accessory or other losses, and using a propeller efficiency of 0.88 (from the sizing code). For the LABC (unlike the other two designs) the RC model was not adjusted to match the CAMRAD II performance at the design conditions, because in order to obtain a converged design from the sizing code, it was necessary to assume a rotor effective L/D substantially larger than that obtained from the comprehensive analysis. It is anticipated that significant improvements in the calculated L/D can be realized using specially designed airfoils, thereby making the comprehensive analysis calculations closer to the performance on which the RC design was based.

DESIGN OPTIMIZATION

Table 15 compares the baseline designs for the LCTR, LCTC, and LABC, in terms of the following metrics:

a) aircraft mission gross weight (lb)
b) installed engine power (hp)
c) mission fuel (lb)
d) purchase price ($M)
e) direct operating cost DOC+I (cents/ASM)

The fuel weights in Table 9 include the reserves. Sensitivity studies were conducted using the sizing code, to optimize the designs by examining variations in disk loading and number of blades. The influence of hover tip speed and cruise tip speed were also examined, considering in particular the noise requirements.

TECHNOLOGY PAYOFF

The impact and payoff of advanced technology were quantified using the sizing code. For this purpose, the technology factors were changed from values representing advanced technology to values representing current technology. The technology factors for weights are given in Table 5, and the engine model is described in Table 6. Table 16 shows the percentage increase (a negative value is good) in the five metrics, caused by removal of various aspects of the advanced technology from the design assumptions. Results are given for the LCTR and LCTC, but not for the LABC because of the level of maturity of the sizing code for that configuration. Table 16 shows the impact of rotor blade and hub weight reduction, and the impact of all structural weight reductions (blade, hub, fuselage, and wing). Individually the hub weight, fuselage weight, and wing weight had small influence; collectively they contribute the significant influence shown in Table 16. Table 16 shows the impact of drag reductions, and the impact of all aerodynamics (drag, rotor figure of merit and cruise efficiency, and download). Individually the hover figure of merit, cruise efficiency (propulsive efficiency for LCTR, rotor drag for LCTC), and download had small influence; collectively they contribute the significant influence shown in Table 16. Table 16 shows the major impact engine technology has on the designs. Increases in vibration treatment weight and acoustic treatment weight were also examined, and found to have a small impact on the metrics.

A conservative design approach, based on past aircraft design experience, would increase the estimated power required (and hence fuel burned) by 25%, and increase the estimated empty weight by 15%, for a fixed payload and performance requirement. The penalty for imposing these weight and power contingencies is shown in Table 16. As the need for large contingencies is attributed to lack of accuracy of current design and analysis tools, Table 16 shows the economic payoff possible by improving these tools.

Figure 17 shows the costs for the LCTR with and without the cost technology factors, and Figure 18 presents the corresponding DOC+I breakdown. These results emphasize and quantify the importance of controlling the maintenance costs for heavy lift rotorcraft.

DESIGN REFINEMENTS

Since the engine model used was intended to represent an advanced engine based largely on currently available technology, it was prudent to examine the impact of higher

SFC. Table 17 compares the baseline designs with the designs obtained when the engine SFC was increased by 10%: the mission fuel increased by about 15%, and the other metrics increased by about 5%.

It is possible that achieving the noise goals will require that the blade passage frequency be kept in the audible range. Table 18 compares the baseline designs with the designs obtained when the blade passage frequency is raised to 20 Hz. For the LCTR, it was necessary to increase the number of blades and increase the disk loading. The increased disk loading results in an increase in all metrics except gross weight. The sizing code model for blade and control weight implies a reduction in rotor weight as the number of blades increases, resulting in a decrease in the aircraft gross weight. For the LCTC, it was necessary to increase the number of blades, but disk loading of the baseline design was already higher than that of the tiltrotor. Hence the reduction of blade weight caused by the increased number of blades results in a reduction of all metrics for the LCTC. These rotor weight trends must be confirmed, but the results of Table 18 suggest that a blade passage frequency of 20 Hz could be an acceptable requirement.

ASSESSMENT OF CONFIGURATIONS

For the NASA civil mission, the Large Civil Tiltrotor (LCTR) had the best cruise efficiency, hence the lowest weight and lowest cost. The LCTR is the configuration with the most promise to meet the NASA technology goals.

The Large Civil Tandem Compound (LCTC) had good cruise efficiency, but less than the tiltrotor, and higher development risk than the tiltrotor. Single main rotor and tandem rotor configurations were comparable in efficiency and risk. Even if reaction drive produced the smallest slowed-rotor compound rotorcraft, the high installed power compromises efficiency, and the reaction drive system has higher noise and substantially increased risk.

The Large Advancing Blade Concept (LABC) had lower cruise efficiency than the tiltrotor for the NASA civil mission.

The LCTR design presented was economically competitive with comparable fixed wing aircraft, with the potential for substantial impact on the air transportation system. The keys to achieving a competitive aircraft are: low drag airframe and low disk loading rotors; structural weight reduction, for both airframe and rotors; drive system weight reduction; improved engine efficiency; low maintenance design; and manufacturing cost comparable to CTOL aircraft.

Thus the LCTR design demonstrated the potential for achieving the Rotorcraft Sector goals of Table 1. With a disk loading of 10 lb/ft^2 compared to the state-of-the-art value of 20 lb/ft^2, the 40% increase in hover efficiency was attained. Considering the OEI hover power (power from 3 out of 4 engines), the power loading was W/P = 6.0. At the cruise conditions, the aircraft lift-to-drag ratio was L/D = 14.5 (Table 12), exceeding the 44% improvement goal. The airframe drag was estimated to be $D/q = 1.5/(W/1000)^{2/3}$ (Table 10). The weight technology factors (Table 5) led to about 22% reduction in gross weight (Table 16), from a 30% reduction in empty weight, which was consistent with the goal of a 25% reduction in empty weight excluding engines. The design had an empty weight fraction of 0.65 (Table 9), or 0.62 excluding engines, so technology countered the growth in empty weight fraction with aircraft size and speed. The calculated noise was 9.3 EPNdB below certification requirements, compared to the goal of 14 EPNdB, with active control and flight operations available to obtain the full reduction as well as deal with low frequency noise.

RISK REDUCTION FOR HEAVY LIFT ROTORCRAFT

The NASA Heavy Lift Rotorcraft Systems Investigation was a focused and coordinated analytical effort to select the best configuration for meeting the Rotorcraft Sector vehicle technology goals. During the course of the investigation, high risk areas were identified. The definition of high risk is one or both of the following: capability or attribute unavailable today, so it is necessary to assume advanced technology will be available in the future in order for the aircraft to achieve the technology goals; or cost prevents the vehicle from being economically competitive, so the payoff of advanced technology is essential to achieving the goals. The following were identified as high risk areas for heavy lift rotorcraft:

a) High torque, light weight drive system.
b) High performance, structurally efficient rotor/ wing system.
c) Low noise aircraft.
d) Super-integrated vehicle management system.

Plans were then developed to mitigate the above risks. The risk reduction plans provide the strategic direction to support a heavy-lift rotorcraft development.

STRATEGIC DIRECTION

The strategic direction provides guidance for selecting highest priority activities, aimed at the four highest risk areas of heavy lift rotorcraft development. Note that there are some important and difficult tasks that are yet not high risk, including rotor aerodynamic design and optimization, rotor and wing airfoil design, airframe aerodynamics, and airframe structures.

HIGH TORQUE, LIGHT WEIGHT DRIVE SYSTEM

Innovative design is required for low drive system weight. Large size implies high torque and high weight fraction, hence drive system weight reduction is essential for an efficient and economical aircraft. The focus must be on design concept, advanced-technology components, and materials.

Low maintenance is required for low operating cost. Low maintenance must be a primary design requirement, even ahead of weight and performance.

High flight speed requires, or at least benefits from, a variable speed propulsion system design. First it is necessary to establish the speed range available from advanced engine technology, and to define the engine required for the heavy lift rotorcraft concept.

HIGH PERFORMANCE, STRUCTURALLY EFFICIENT ROTOR/WING SYSTEM

Innovative rotor and wing design is required, probably with unconventional dynamics. Large size implies high weight fraction, high speed introduces stability issues, and good rotor system performance is essential for an efficient and economical aircraft. The focus must be on integrated rotor/wing performance and dynamic behavior.

Structural efficiency is required for low rotor and hub and wing weight. The focus must be on design concepts for durability and damage tolerance.

Low maintenance is required for low operating cost. Low maintenance must be a primary design requirement, even ahead of weight and performance.

LOW NOISE AIRCRAFT

New approaches are required to meet the challenge of low noise. Large size implies low frequency noise and expanded acoustic footprint. An understanding of heavy lift vehicle acoustic phenomena (low frequency and relative distance to community) is required, including psychoacoustics for low frequency. New rotor design guidelines and annoyance metrics must be developed. The focus must be on a combination of rotor design, active control, and flight operations.

SUPER-INTEGRATED VEHICLE MANAGEMENT SYSTEM

Broad spectrum active control is required for an effective heavy lift rotorcraft. Large size implies a significant influence of low frequency airframe elastic modes on flight dynamics. Active control is required to achieve the goals of low rotor-induced vibration and noise. Safe operation in one-engine inoperative conditions is essential for civil rotorcraft. Rotor load limiting and active control are needed for full utilization of the structural capability in the rotor and airframe. Hence an expanded integration of the vehicle management system is required: a flight control system for good handling qualities and gust response, active control of vibration and noise, and rotor load limiting and active control. The focus must be on load limiting and system integration.

CONCLUSION

The NASA Heavy Lift Rotorcraft Systems Investigation examined in depth several rotorcraft configurations for large civil transport, designed to meet the technology goals of the NASA Vehicle Systems Program. Design and analysis tools were applied to define three configurations: Large Civil Tiltrotor (LCTR), Large Civil Tandem Compound (LCTC), and Large Advancing Blade Concept (LABC).

For the NASA civil mission, the Large Civil Tiltrotor had the best cruise efficiency, hence the lowest weight and lowest cost. Thus the LCTR is the configuration with the best potential to meet the NASA technology goals. The design presented was economically competitive, with the potential for substantial impact on the air transportation system. While fixed wing aircraft for this mission exist, the investigation only showed the potential for a high speed, heavy lift rotorcraft. The keys to achieving a competitive aircraft were low drag airframe and low disk loading rotors; structural weight reduction, for both airframe and rotors; drive system weight reduction; improved engine efficiency; low maintenance design; and manufacturing cost comparable to fixed-wing aircraft.

Risk reduction plans were developed to provide the strategic direction to support a heavy-lift rotorcraft development. The following high risk areas were identified for heavy lift rotorcraft: high torque, light weight drive system; high performance, structurally efficient rotor/wing system; low noise aircraft; and super-integrated vehicle management system.

ACKNOWLEDGMENTS

The NASA Heavy Lift Rotorcraft Systems Investigation was a community effort. The participation by Bell Helicopter, Boeing, and Sikorsky Aircraft is gratefully acknowledged. Contributions by The Pennsylvania State University, University of Maryland, and Georgia Institute of Technology are also much appreciated. The individuals who contributed to the investigation are too numerous to list here, but the authors wish to recognize the following dedicated individuals on the government analysis team: Wally Acree, John Coy, William Decker, Robert Kufeld, Ethan Romander, Johannes van Aken (NASA Ames); Doug Boyd, Casey Burley (NASA Langley); Preston Martin, Rick Peyran, John Preston, Jeff Sinsay, Hyeonsoo Yeo (U. S. Army Aeroflightdynamics Directorate); Robert Handschuh, Kevin O'Brien (U. S. Army – Army Research Laboratory). Finally, the guidance provided by Charles Crawford, Troy Gaffey, Franklin Harris, Robert Loewy, and Kenneth Rosen during the course of this investigation is very much appreciated.

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NOMENCLATURE

A	rotor disk area
c_{do}	mean drag coefficient for profile power
C_T	rotor thrust coefficient, $T/(\rho A V^2_{tip})$
C_W	rotor weight coefficient, $W/(\rho A V^2_{tip})$
D/q	airframe drag divided by dynamic pressure
L/D	aircraft effective lift-to-drag ratio, W/VP (based on cruise power)
M	Mach number
M_{at}	advancing tip Mach number
P	aircraft power
R	rotor radius
T	rotor thrust
V	flight speed
V_{br}	best range flight speed
V_{tip}	rotor tip speed
W	gross weight
W_E	empty weight
W/A	disk loading
κ_{ind}	induced power factor ($P_{induced}/P_{ideal}$)
ρ	air density
σ	rotor solidity (ratio blade area to disk area)
ASM	available seat miles
CTOL	conventional takeoff and landing
DOC	direct operating cost
DOC+I	direct operating cost plus interest

ISA	international standard atmosphere	RIA	runway independent aircraft
LABC	Large Advancing Blade Concept	SFC	specific fuel consumption
LCTC	Large Civil Tandem Compound	SHP	shaft power
LCTR	Large Civil Tilt Rotor	SLS	sea level standard
MCP	maximum continuous power	SOA	state of the art
MRP	maximum rated power	VTOL	vertical takeoff and landing
OEI	one-engine inoperative		

Table 1. Rotorcraft Sector capability set and technology goals.

ROTORCRAFT NOTIONAL VEHICLE 15-YEAR CAPABILITIES	
Payload	120 passengers
Cruise speed	M = 0.60 (350 knots) at 30000 ft
Cruise altitude	at or above 22000 ft (icing)
Range	1200 nm
ROTORCRAFT SECTOR 15-YR TECHNOLOGY GOALS	
Hover efficiency, W/P	6
Efficient Cruise, L/D	12
Empty Weight Fraction	0.41 (excluding engines)
Community Noise	SOA–14 EPNdb
Flight Control	Automated single-pilot CAT IIIC SNI for heavy lift
Advanced Engine Performance	SFC = SOA*0.9, SHP/W = SOA*1.2
Cabin Noise and Vibration	77dBA & 0.05g

Table 2. Civil design mission.

1200 nm range, 120 passengers
Cruise at 350 knots and 30000 ft (min 22000 ft, for icing)
Design mission
- Idle 5 min
- Takeoff + 1 min Hover OGE — 5k ISA+20^{o}C
- [convert]
- Climb at V best range (0k ISA to 30k ISA, distance part of range)
- Cruise at 350 knots, for 1200nm range — 30k ISA
- Reserve: 30 min + 30 nm at V_{br} — 30k ISA
- Descend at V_{br} (no range credit)
- [convert]
- 1 min Hover OGE + Landing — 5k ISA+20^{o}C
- Idle 5 min

Design power
- Hover: 95% MRP, 5k ISA+20^{o}C
- Cruise: 100% MCP, 30k ISA
- One engine inoperative (OEI):
  - at 5k ISA+20^{o}C, 133% (OEI MCP) greater than 90% (HOGE P_{req})
  - at 22k ISA, (OEI MCP) greater than (P_{req} at V_{br})
  - 4 engines

Table 3. Payload and fuselage.

Payload: 120 passengers = 26400 lb
Passengers: 120 at 220 lb each
(190 + 30 baggage)
Flight crew: 2 at 240 lb each
Cabin crew: 3 at 210 lb each
Fuselage size and layout
12 first class (4x3, 38 in pitch)
108 economy class (6x18, 32 in pitch)
Length = 109.61 ft, width = 12.25 ft

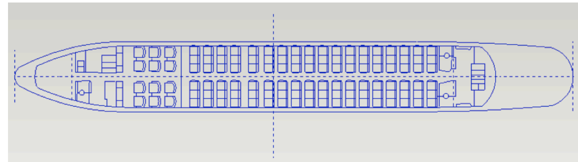

Table 4. Critical design conditions for aeromechanics analysis.

Blade stability
Thrust sweep in hover (SLS), to rotor stall
Level flight speed sweep (30k ISA), to maximum power
Aircraft and rotor stability
Up to 350 knots at SLS, 500 knots at 30k ISA
flutter speed 1.2 V_{dive} = 1.2 (1.25 V_{cruise}) = 1.50 V_{cruise} = 525 knots (FAR)
flutter speed V_L = 1.15 (1.2 V_{cruise}) = 1.38 V_{cruise} = 480 knots (MIL-A-8870)
Tiltrotor high speed forward flight
Zero and max power; sea level, 30k; symmetric and antisymmetric modes, with drive train
Ground resonance and air resonance for soft-inplane rotors
Performance
Thrust sweep in hover (5k ISA+20^{o}C), for power and figure of merit
Speed sweep in high speed forward flight (30k ISA) for power and efficiency
Loads (blade, hub, control), deflection, and vibration
Load factor sweep at 80 knots (SLS), to 1.5g
Level flight speed sweep (5k ISA+20^{o}C), to maximum power
Nacelle angles of 80, 60 deg for tiltrotor

Table 5. Weight technology factors used for aircraft sizing.

Rotor blade weight	0.79
Rotor hub weight	0.96
Drive system weight	0.67
Fuselage weight	0.88
Wing primary structure weight	0.88
Empennage weight	0.90

Table 6. Engine technology used for aircraft sizing.

		current technology	advanced technology
SFC (SLS MCP)	lb/shp-hr	0.4260	0.3243
specific power (MCP)	hp/lb/sec	140.8	290.0
power/weight	shp/lb	6.49	7.48
Relative SLS MRP			
MRP at 5k ISA+20°C	ratio shp	0.769	0.769
MCP at 30k ISA	ratio shp	0.348	0.348
Fuel flow at 5k ISA+20°C	ratio lb/hr	0.781	0.781
Fuel flow at 30k ISA	ratio lb/hr	0.334	0.334

Table 7. Advanced technology estimates.

		LCTR	**LCTC**	**LABC**
		tiltrotor	tandem compound	advancing blade concept
Specified				
Hover C_W/σ, (5k ISA+20°C)		0.141	0.141	0.100
Hover C_W/σ, (4k/95 °F)		0.140	0.140	0.100
Hover download		9.7%	5.7%	5.5%
Tip speed, hover	ft/sec	650	650	650
Tip speed, cruise	ft/sec	350	205	255
Cruise speed, 30k	knots	350	350	350
Drag, D/q / $(W/1000)^{2/3}$	ft^2	1.5	1.9	1.3
Wing loading	lb/ft^2	80	80	—
Optimum				
Disk loading, W/A	lb/ft^2	10	15	20
Maximum M_{at}		0.70	0.80	0.85
Cruise tip speed	ft/sec	350	205	255

Table 8. Heavy Lift Rotorcraft Designs.

	LCTR	**LCTC**	**LABC**
	tiltrotor	tandem compound	advancing blade
Mission gross weight (lb)	123562	138764	160636
Engines (hp)	4x6914	4x9684	4x14267
Rotor diameter (ft)	88.7	76.7	90.5
Disk loading W/A (lb/ft^2)	10	15	25
C_W/σ (geom, 5k ISA+20^{o}C)	0.133	0.133	0.0675
C_W/σ (T-wt, 5k ISA+20^{o}C)	0.141	0.141	0.090
Hover tip speed (ft/sec)	650	650	650
Cruise tip speed (ft/sec)	350	205	255
maximum M_{at}	0.70	0.80	0.85
Solidity	0.0881	0.1321	0.1721
Number blades per rotor	4	4	5
chord (75%R, ft)	3.06	3.98	4.89
aspect ratio	14.5	9.6	9.2
taper ratio	0.8	0.8	0.33
Drag D/q (ft^2)	37.3	50.3	38.1
$(D/q)/(W/1000)^{2/3}$	1.5	1.9	1.3
Wing loading (lb/ft^2)	80	80	–
area (ft^2)	1545	1735	–
span (ft)	105	144	–
aspect ratio	7.1	12.0	–
Mission, payload	120 pass	120 pass	120 pass
range (nm)	1200	1200	1200
cruise altitude (ft)	30000	30000	30000
cruise speed (kt)	350	350	350
Cruise power (hp)	11904	15956	25068
Cruise L/D=WV/P	11.1	9.3	6.9

Table 9. Concept weight comparison.

	LCTR	LCTC	LABC
GROSS WEIGHT	123562	138762	160636
weight empty fraction	65.3%	65.6%	64.7%
WEIGHT EMPTY	80701	91079	103991
FIXED WEIGHT	13583	13583	13583
SCALED WEIGHT	67119	77497	90408
Structure	36104	41668	47529
Wing Group	8804	11998	0
Primary Thruster	13714	11494	24572
Tail / Aux Thrust	594	2870	4135
Body Group	7072	10194	11596
Landing Gear Group	3228	3625	4197
Nacelle	2422	1091	2411
Air Induction	270	397	617
Propulsion	18373	24928	29021
Engine installation	4540	6446	9284
Fuel System	556	957	887
Drive System	13277	17525	18850
Flight Controls	4927	4628	5238
Other Scaled Weight	7716	6273	8621
USEFUL LOAD	42860	47684	56645
Crew	1110	1110	1110
Fixed Useful Load	100	100	100
Fluids	240	240	240
Fuel	15010	19834	28795

Table 10. Cruise drag buildup.

	LCTR	LCTC	LABC
Wing D/q	14.10	15.84	—
area	1545	1735	
C_D	.0091	.0091	
Body D/q	11.88	12.42	12.38
S_{wet}	3650	3650	4290
C_f	.0021	.0021	.0021
interference	4.32	4.86	3.50
Horizontal Tail D/q	1.33	1.91	1.37
area	180	217	186
Vertical Tail D/q			1.33
Pylon D/q	10.02	9.39	9.45
Hub D/q		10.72	13.45
hub D/q / $(W/1000)^{2/3}$		0.40	0.45
Total D/q	37.33	50.28	38.06
D/q / $(W/1000)^{2/3}$	1.50	1.88	1.29
Gross Weight	123562	138764	160636
Hover Download (%T)	9.7%	5.7%	5.5%

Table 11. Heavy lift rotorcraft characteristics.

	LCTR	LCTC	LABC
Design gross weight (lb)	123562	138764	160636
Total cruise drag, D/q (ft^2)	37.3	50.3	38.1
Disk loading, W/A (lb/ft^2)	10	15	25
Hover C_W/σ (T-wt, 5k ISA+20°C)	0.141	0.141	0.090
Hover download	9.7%	5.7%	5.5%
Rotor radius (ft)	44.35	38.37	45.22
Number of blades per rotor	4	4	5
Solidity (thrust weighted)	0.0881	0.1321	0.1721
Chord (75%R ft)	3.07	3.98	4.89
Maximum M_{at}	0.70	0.80	0.85
Tip speed (ft/sec), hover	650	650	650
Tip speed (ft/sec), cruise	350	205	255
Rotor speed (rpm), hover	140	162	137
Rotor speed (rpm), cruise	75	51	54
Blade taper	0.8	0.8	2 & 1/3
Blade twist (deg), inboard of 50%R	–32	0	2
Blade twist (deg), outboard of 50%R	–30	–12	–12
Lock number	12.1	13.0	19.1
Single blade weight (lb), from blade structural design	745	646	1080
Total blade weight (lb), all rotors	5960	5168	10800
data source and identification			
size, airframe aerodynamics: from RC code	5/13/05	4/22/05	5/12/05
blade stiffness, inertia: from structural design	6/17/05	5/13/05	7/18/05
airframe structural dynamics: from NASTRAN model	5/05	5/05	5/05
rotor airfoils	current technology airfoils, with Reynolds number correction of drag, and with stall delay for LCTR		

Table 12. Comparison of LCTR rotor performance from RC (sizing) and CAMRADII (comprehensive analysis).

	HOVER 5k ISA+20°C, 650 ft/sec		CRUISE 350 knots, 30k ISA, 350 ft/sec V/V_{tip} = 1.688, M_{at} = 0.70	
	RC	CAMRADII	RC	CAMRADII
Thrust	136836	136751	8531	8538
C_T/σ	0.1557	0.1556	0.0720	0.0720
Power	17061	17155	11283	11296
Parasite power			9163	9170
Induced power	15879	15967	248	256
Profile power	1182	1186	1875	1869
κ_{ind}	1.186	1.193	24.323	25.125
c_{do}	0.0091	0.0091	0.0087	0.0087
Figure of merit	0.785	0.780		
Propulsive efficiency			0.812	0.812
L/D = WV/P			11.76	11.75

Table 13. Comparison of LCTC rotor performance from RC (sizing) and CAMRADII (comprehensive analysis).

	HOVER 5k ISA+20°C, 650 ft/sec		CRUISE 350 knots, 30k ISA, 205 ft/sec V/V_{tip} = 2.882, M_{at} = 0.80	
	RC	CAMRADII	RC	CAMRADII
Thrust	147102	146914	13608	12812
C_T/σ	0.1491	0.1489	0.2981	0.2806
Power	23803	23513	0	16
Induced power	22520	22237	462	442
Profile power	1283	1276	2280	2348
κ_{ind}	1.305	1.291	13.332	14.389
c_{do}	0.0088	0.0088	0.0101	0.0104
Figure of merit	0.725	0.732		
Rotor drag			2553	2583
Rotor D/q			16.5	16.7
L/D = WV/P			9.9	9.8

Table 14. Comparison of LABC rotor performance from RC (sizing) and CAMRADII (comprehensive analysis).

	HOVER 5k ISA+20°C, 650 ft/sec		CRUISE 350 knots, 30k ISA, 255 ft/sec V/V_{tip} = 2.319, M_{at} = 0.85	
	RC	CAMRADII	RC	CAMRADII
Thrust	169960	170592	159068	159192
C_T/σ	0.0952	0.0955	1.2468	1.2478
Rotor shaft power	32497	37961	0	-2554
Induced power	30482	35940		11224
Profile power	2015	2022		11963
Ind+pro power			14251	23188
κ_{ind}	1.186	1.390		3.221
c_{do}	0.0076	0.0077		0.0280
Figure of merit	0.791	0.681		
Drag			13268	23997
Rotor L/D_e			12.0	7.7
L/D = WV/P			7.2	5.1

Table 15. Comparison of baseline designs.

	LCTR	LCTC	LABC
Gross weight (lb)	123562	138762	160636
Engine power (hp)	4x6914	4x9684	4x14267
Mission fuel (lb)	13624	17902	26008
Purchase price ($M)	61.9	84.5	116.8
DOC (cents/ASM)	13.3	17.2	23.6

Table 16. Impact of technology on the designs: percentage increase caused by changing the technology from advanced to current level.

	weight	power	fuel	price	DOC
LCTR					
Blade weight	12	13	11	16	13
All structural weight	21	22	18	27	22
Drive system weight	23	24	21	29	25
Airframe drag (+25%)	6	14	14	12	10
All aerodynamics	10	20	21	17	16
Engine technology	23	28	70	28	29
Weight and power contingency	13	25	25	22	19
LCTC					
Blade weight	9	9	8	11	10
All structural weight	20	20	18	24	22
Drive system weight	29	28	26	35	31
Airframe drag (+25%)	5	10	13	8	8
Hub drag	9	22	24	17	16
All aerodynamics	17	38	39	31	28
Engine technology	48	63	124	60	61
Weight and power contingency	13	25	25	22	20

Table 17. Influence of increased engine SFC.

	LCTR baseline	increased SFC	**LCTC** baseline	increased SFC
Engine SFC	100%	110%	100%	110%
Gross weight (lb)	123652	128555	138764	145928
Engines (hp)	4x6914	4x7198	4x9684	4x10167
Disk Loading (lb/ft^2)	10	10	15	15
Rotor diameter (ft)	88.7	90.5	76.7	78.7
Rotor solidity	0.0881	0.0881	0.1321	0.1321
Number blades per rotor	4	4	4	4
Chord (75%R, ft)	3.06	3.13	3.98	4.08
Blade aspect ratio	14.5	14.5	9.6	9.6
Rotor weight (lb)	13714	14449	11494	12285
Mission Fuel (lb)	13624	15528	17902	20652
Increase Relative Baseline				
Gross weight		4%		5%
Power		4%		5%
Mission fuel		14%		15%
Price		4%		5%
DOC		5%		6%

Table 18. Influence of increased rotor blade passage frequency.

	LCTR baseline	increased BPF	**LCTC** baseline	increased BPF
Blade passage freq (Hz)	9.3	19.8	10.8	20.1
Gross weight (lb)	123652	117261	138764	129857
Engines (hp)	4x6914	4x8137	4x9684	4x9417
Disk Loading (lb/ft^2)	10	14	15	16
Rotor diameter (ft)	88.7	73.0	76.7	71.9
Rotor solidity	0.0881	0.1233	0.1321	0.1410
Number blades per rotor	4	7	4	7
Chord (75%R, ft)	3.06	2.02	3.98	2.28
Blade aspect ratio	14.5	18.1	9.6	15.8
Rotor weight (lb)	13714	9738	11494	9295
Mission Fuel (lb)	13624	14373	17902	16792
Increase Relative Baseline				
Gross weight		–5%		–6%
Power		18%		–3%
Mission fuel		6%		–6%
Price		5%		–6%
DOC		3%		–6%

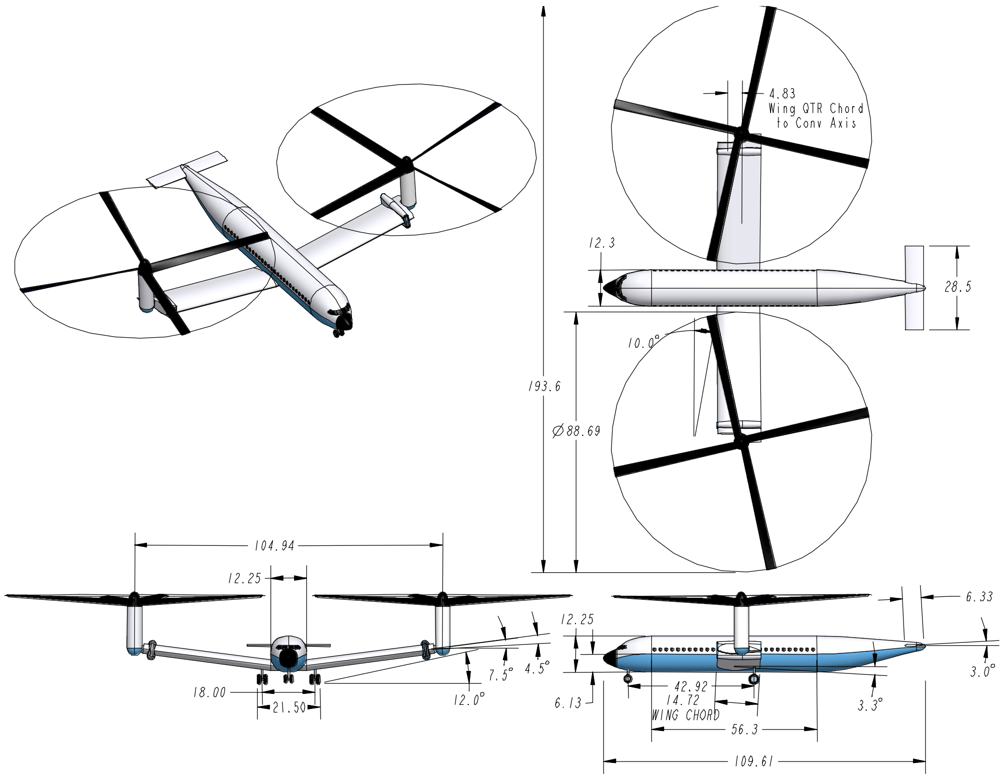

Figure 1. Three-view of Large Civil Tiltrotor (LCTR).

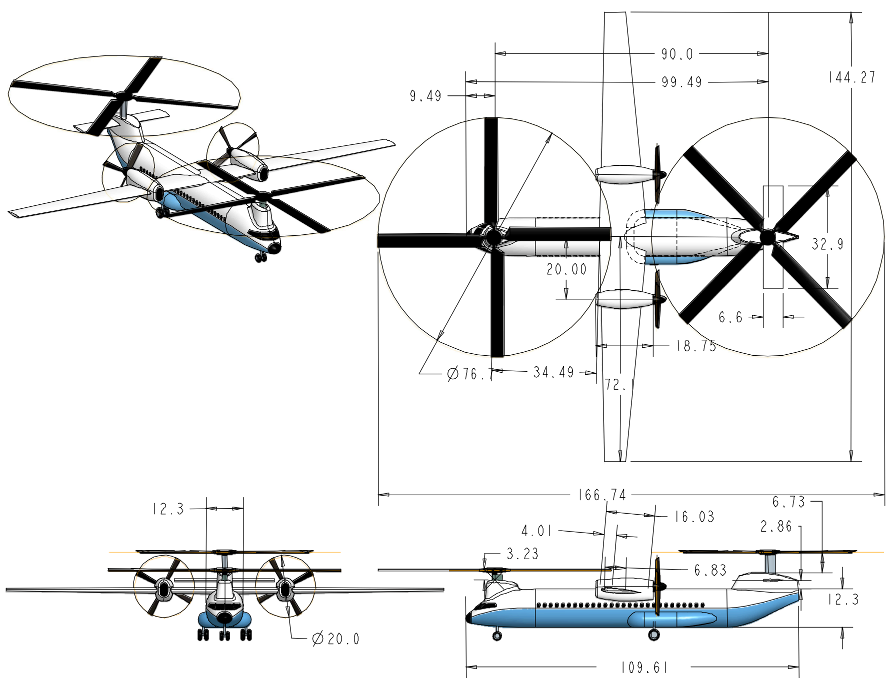

Figure 2. Three-view of Large Civil Tandem Compound (LCTC).

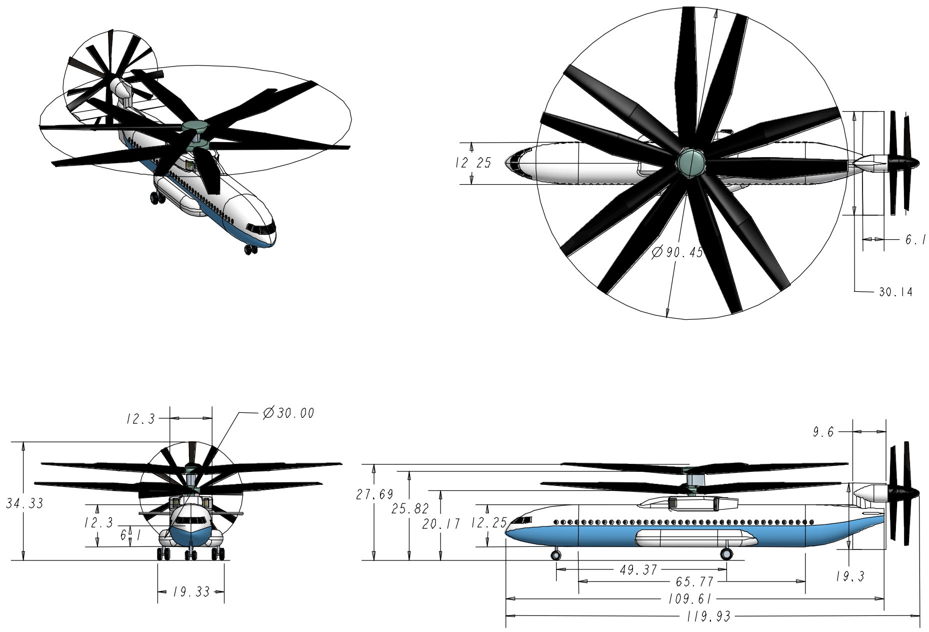

Figure 3. Three-view of Large Advancing Blade Concept (LABC)

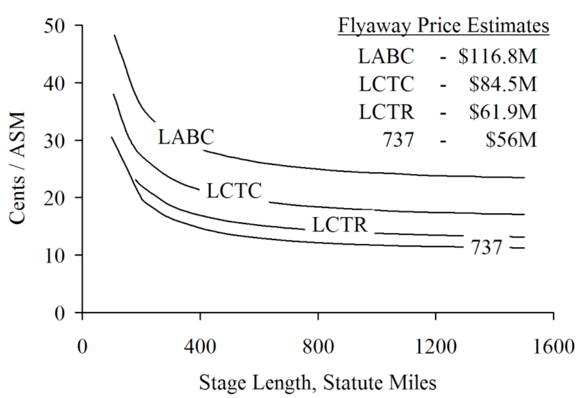

Figure 4. Flyaway price (2005 USD) and DOC+I (2005 cents/ASM) comparisons for baseline designs.

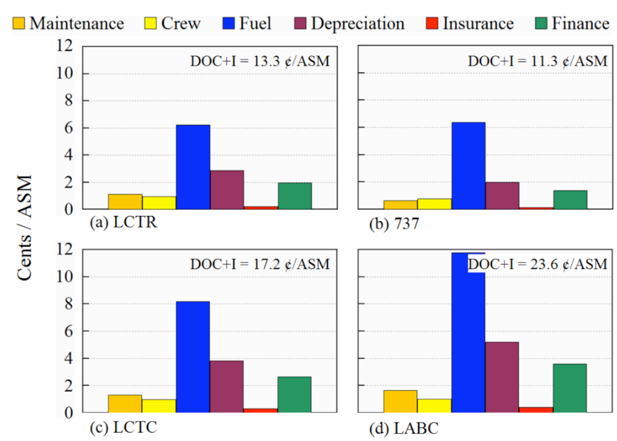

Figure 5. Cost elements compared for heavy lift rotorcraft and B737 (1,200 nm, 120 passengers, including technology factors for rotorcraft costs).

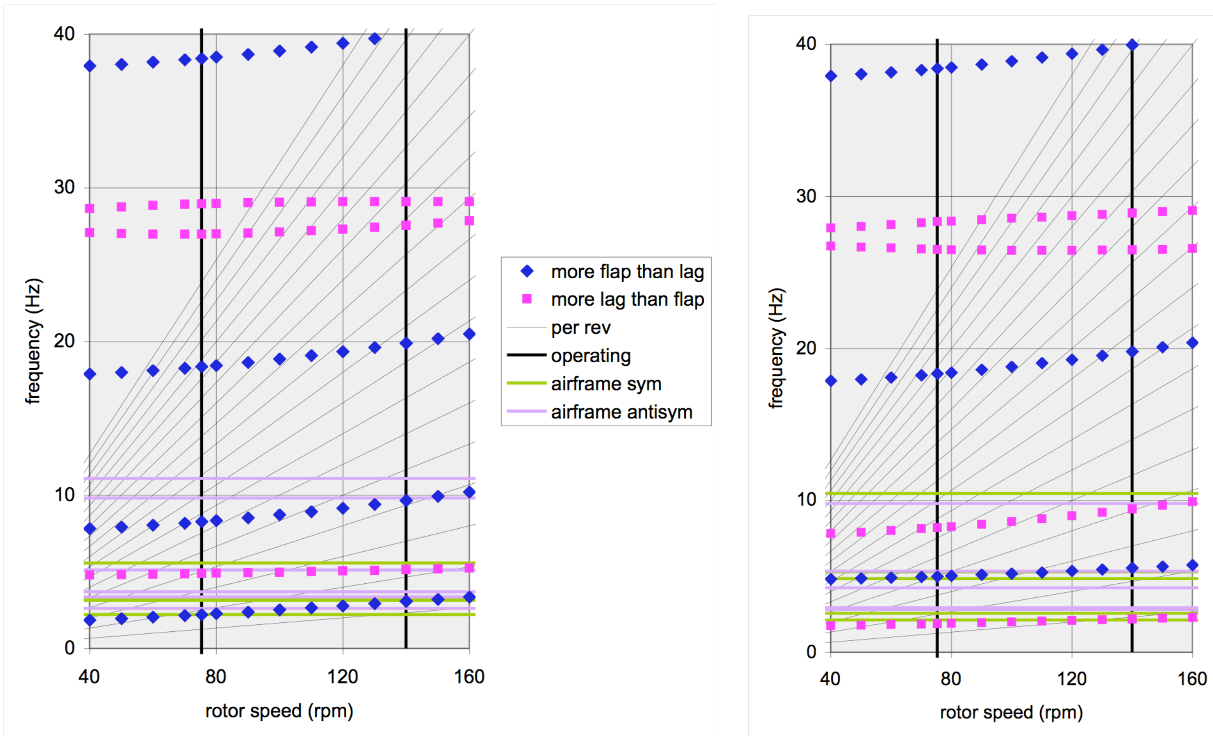

Figure 6. LCTR blade and airframe frequencies. Collective = 0 deg (left figure, appropriate for 140 rpm operation) and collective = 60 deg (right figure, 75 rpm operation).

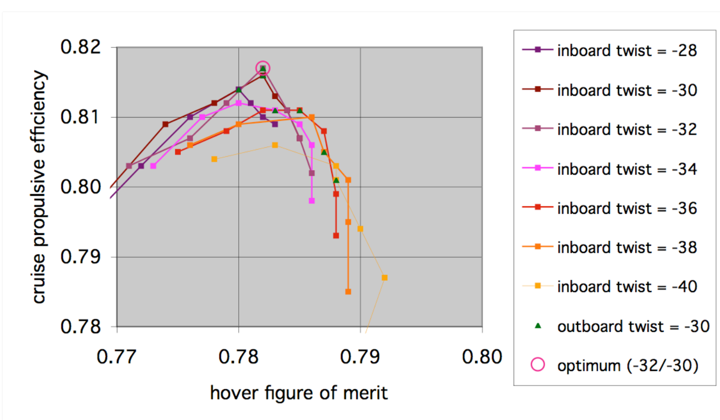

Figure 7. LCTR twist optimization.

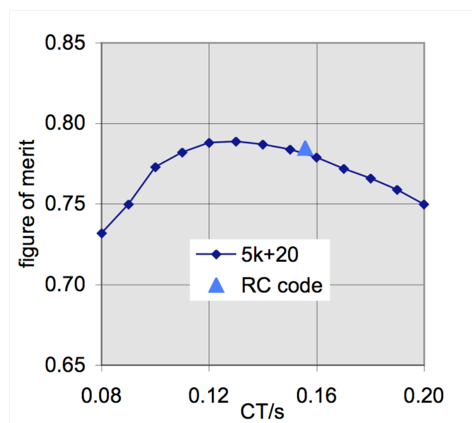

Figure 8. LCTR rotor hover performance.

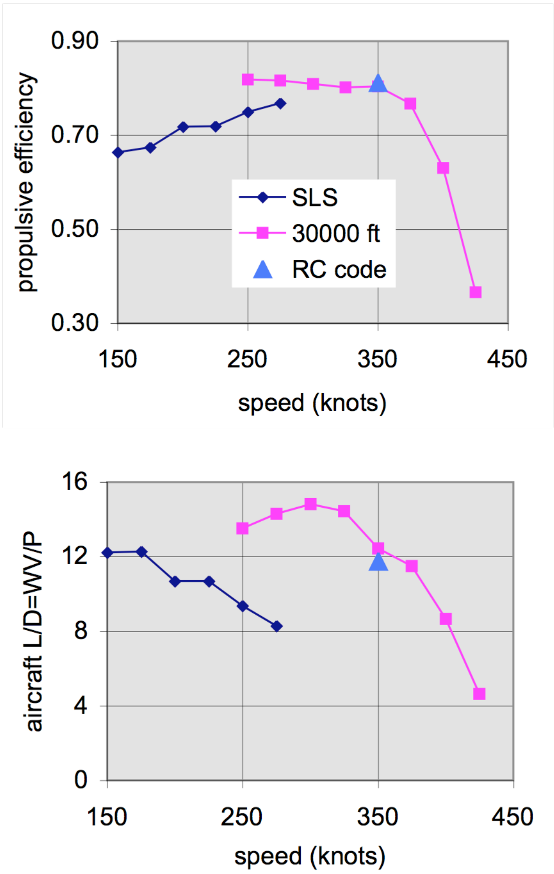

Figure 9. LCTR rotor cruise performance.

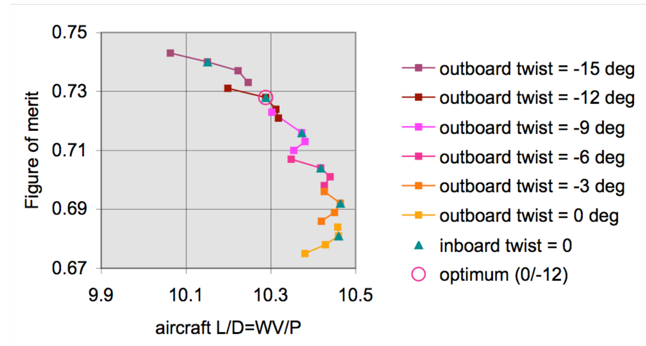

Figure 11. LCTC twist optimization.

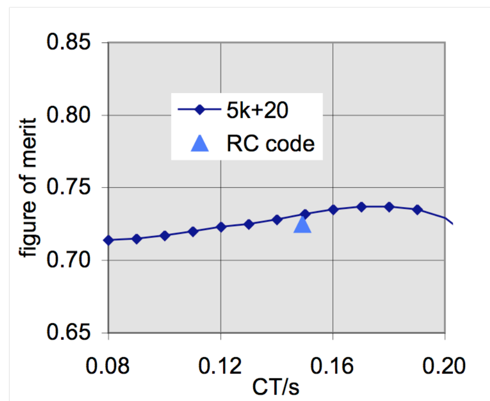

Figure 12. LCTC rotor hover performance.

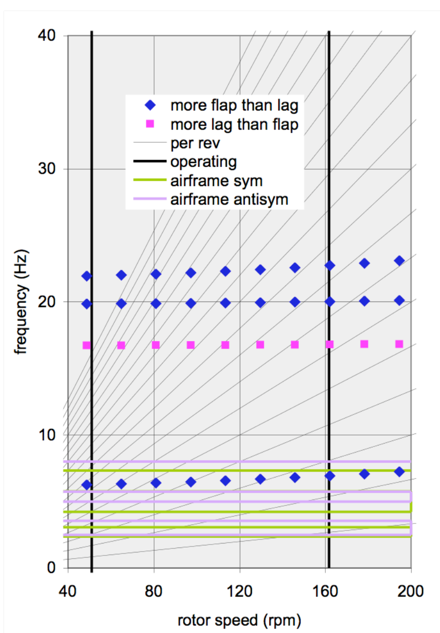

Figure 10. LCTC blade and airframe frequencies (collective = 10).

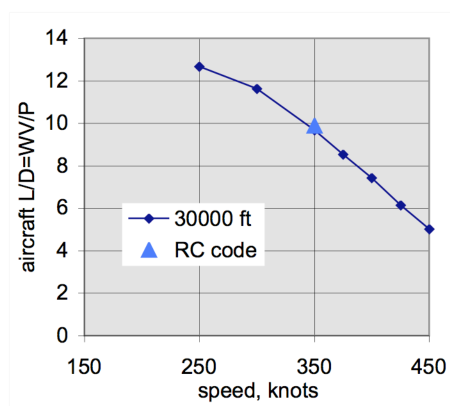

Figure 13. LCTC aircraft cruise performance.

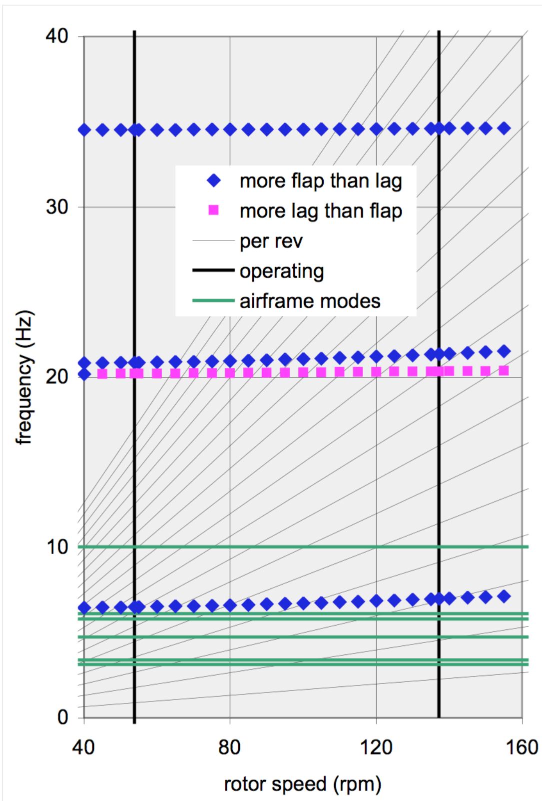

Figure 14. LABC blade and airframe frequencies (collective = 0).

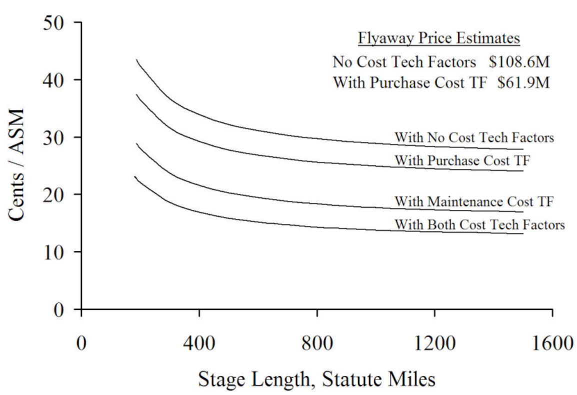

Figure 17. Effect of cost technology factors on flyaway price (2005 USD) and DOC+I (2005 cents/ASM) for LCTR.

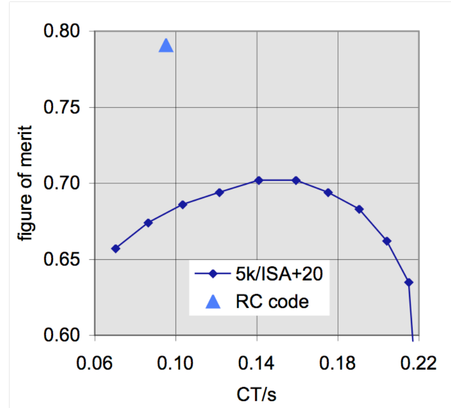

Figure 15. LABC rotor hover performance.

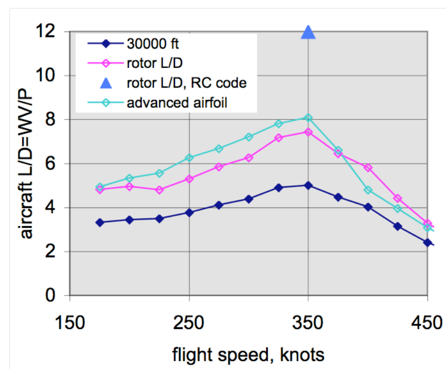

Figure 16. LABC aircraft cruise performance.

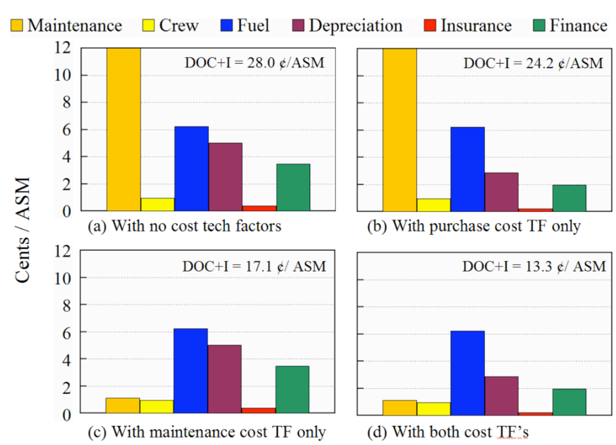

Figure 18. Cost elements compared for LCTR with and without cost technology factors (1,200 nm, 120 passengers)