

Influence of Alternative Engine Concepts on LCTR2 Sizing and Mission Profile

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Abstract

The Large Civil Tiltrotor (LCTR) was developed as part of the NASA Heavy Lift Rotorcraft Systems Investigation in order to establish a consistent basis for evaluating the benefits of advanced technology for large tiltrotors. The concept has since evolved into the second-generation LCTR2, designed to carry 90 passengers for 1,000 nm at 300 knots, with vertical takeoff and landing. This paper examines the impact of advanced propulsion system concepts on LCTR2 sizing. Two concepts were studied: an advanced, single-speed engine with a conventional power turbine layout (Advanced Conventional Engine, or ACE), and a variable-speed power turbine engine (VSPT). The ACE is the lighter engine, but requires a multi-speed (shifting) gearbox, whereas the VSPT uses a lighter, fixed-ratio gearbox. The NASA Design and Analysis of Rotorcraft (NDARC) design code was used to study the trades between rotor and engine efficiency and weight. Rotor performance was determined by Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics (CAMRAD II), and engine performance was estimated with the Numerical Propulsion System Simulation (NPSS). Design trades for the ACE vs. VSPT are presented in terms of vehicle weight empty for variations in mission altitude and range; the effect of different One Engine Inoperative (OEI) criteria are also examined. Because of its strong effect on gearbox weight and on both rotor and engine efficiency, rotor speed was chosen as the reference design variable for comparing design trades. The two propulsion concepts had nearly identical vehicle weights and mission fuel consumption, and their relative advantages varied little with cruise altitude, mission range, or OEI criteria; high cruise altitude and low cruise tip speed were beneficial for both concepts.

Notation

A	rotor disk area	η_t	power turbine efficiency
c_{do}	section profile drag coefficient	κ	induced velocity factor
C_T	rotor thrust coefficient, $T/(\rho AV_{tip}^2)$	ρ	air density
C_W	rotor weight coefficient, $W/(\rho AV_{tip}^2)$	σ	rotor solidity (thrust-weighted)
D	drag	ACE	Advanced Conventional Engine
e	Oswald efficiency factor	CAMRAD	Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics
FM	figure of merit	CRP	Contingency Rated Power
L	lift	EIS	Entry Into Service
L/D_e	aircraft lift over equivalent drag, W/P	HOGE	Hover Out of Ground Effect
P	power required	ISA	International Standard Atmosphere
q	dynamic pressure	KCAS	Knots Calibrated Airspeed
T	rotor thrust	LCTR2	Large Civil Tilt Rotor—iteration 2
V	airspeed	MCP	Maximum Continuous Power
V_{br}	aircraft best-range speed	MRP	Maximum Rated Power (take-off power)
V_{tip}	rotor tip speed	NDARC	NASA Design and Analysis of Rotorcraft
W	gross weight	NPSS	Numerical Propulsion System Simulation
WE	weight empty	OEI	One Engine Inoperative
η_p	propulsive efficiency, TV/P	OGE	Out of Ground Effect
		SFC	Specific Fuel Consumption
		SNI	Simultaneous Non-Interfering approach
		VSPT	Variable Speed Power Turbine engine:
			FG: fixed geometry
			VG: variable geometry
		WATE	Weight Analysis of Turbine Engines

Presented at the American Helicopter Society Future Vertical Lift Aircraft Design Conference, San Francisco, CA, January 18-20, 2012. This is a work of the U. S. Government and is not subject to copyright protection in the U.S.

Introduction

The Large Civil Tiltrotor (LCTR), was developed as part of the NASA Heavy Lift Rotorcraft Systems Investigation (Ref. 1). The concept has since evolved into the second-generation LCTR2, described in detail in Refs. 2 and 3. The LCTR2 design goal is to carry 90 passengers for 1,000 nm at 300 knots, with vertical takeoff and landing. The overall purpose of the design effort is to develop a consistent basis for evaluating the benefits of advanced technology for large tiltrotors. This paper examines the impact of advanced engine and gearbox concepts on mission performance, and presents a criterion for making the tradeoff between a variable-speed power turbine (VSPT) engine and a multi-speed (shifting) gearbox.

A major challenge in the design of any tiltrotor is selection of the optimum rotor tip speed. Ideally, tip speed would vary widely throughout the flight envelope, conceivably by more than 50% of hover tip speed. This puts severe demands upon engine and gearbox designs. Following Ref. 1, LCTR2 hover tip speed is fixed at 650 ft/sec to reduce noise, leaving cruise tip speed—or equivalently, rotor rpm—as the critical variable.

The engine/gearbox combination cannot be chosen independently of the rotor design. High rotor rpm reduces drive-train torque, hence weight, but the associated high tip speed reduces rotor efficiency in cruise. With a fixed-ratio gearbox, rpm also affects engine efficiency and power capability. Both rotor and engine performance are further affected by cruise altitude and the radically different requirements for efficient cruise and emergency conditions (OEI) in hover. There is therefore a multidimensional tradeoff between rotor efficiency, engine efficiency, gearbox weight, and engine weight, all varying with the mission profile.

The motivation of this paper was to explore the implications of the rotor/engine/gearbox tradeoff, with the expectation of developing an updated mission profile consistent with expected advances in engine technology. It was expected that the result would indicate a clear choice between propulsion concepts (VSPT vs. multi-speed gearbox), but as will be shown, the choice is closely dependent upon technology assumptions.

Propulsion Concepts

The original LCTR2 design (Fig. 1) assumed an advanced, but conventional, turboshaft engine combined with a two-speed gearbox to achieve optimum rotor tip speed in cruise while retaining low fuel consumption (good engine specific fuel consumption, or SFC). Since then, studies of advanced engine concepts have evolved to three different technical approaches: an advanced, single-speed engine with conventional power turbine layout (Advanced Conventional Engine, or ACE); and two concepts using variable-speed power turbine (VSPT) technology (Ref. 4) to extend the range of power turbine (and therefore rotor) rpm while

maintaining high power turbine efficiency and work potential. Initial engine options included a variable geometry VSPT (VG-VSPT) with adjustable turbine guide vanes to maximize power turbine rpm variability while maintaining efficiency and operability, but also incurring a significant weight and complexity penalty. A more conventional, fixed-geometry VSPT (FG-VSPT) was also studied. Reference 4 showed that the increased efficiency of the VG-VSPT did not offset the increase in engine weight over the FG-VSPT and resulted in a higher vehicle gross weight.

Figure 2 summarizes the differences in cruise power available at different power turbine speeds for the three concepts, based on engine availability in 2035; Fig. 2 also includes a 2015 (state-of-the-art) engine for reference to differences due to assumed technology level, indicated as year of service entry. The advanced technology, “standard” power turbine engine (ACE) does not result in additional cruise horsepower capability, but achieves a 20% reduction in fuel burn over the 2015 engine.

The ACE has the lowest engine weight, but requires a heavier, multi-speed gearbox. The VG-VSPT has the highest engine weight, but maintains good SFC at reduced rpm and can use a lighter, fixed-ratio gearbox. The FG-VSPT maintains good SFC levels over the engine operating envelope almost as well as the VG-VSPT and could still use the lighter, fixed-ratio gearbox. The FG-VSPT engine has less power capability at low rpm than the VG-VSPT, but this is not an issue for the LCTR2. The VG-VSPT concept is not as well developed as the other engines, hence its data in Fig. 2 are notional.

For the present study, the combinations of engines and gearbox concepts were narrowed to two: the ACE with a two-speed gearbox, and the VSPT with a fixed-ratio gearbox. These represent the propulsion systems most likely to be utilized for LCTR2. Assuming equivalent levels of technology, other combinations would either be too heavy or too inefficient. A different mission profile could possibly favor a variable-geometry engine, so the VG-VSPT remains a candidate for future studies.

Description of Analyses

In order to properly determine the optimum configuration, all subsystem weights and efficiencies must be propagated through the complete aircraft design, typically using a design sizing code. The study reported here utilized the design code NDARC (NASA Design and Analysis of Rotorcraft, Refs. 5-7) to study the trades between rotor and engine efficiency as operating speed (rotor tip speed and engine rpm) is varied, with and without a two-speed gearbox. The higher the cruise tip speed, the lighter the gearbox, and the lower the demands upon engines using a fixed-ratio gearbox. Increased fuel burn in climb must be traded against the benefits of lower drag at high altitude. These effects are all captured by NDARC, using rotor and engine performance models that incorporate the results of CAMRAD II and NPSS analyses.

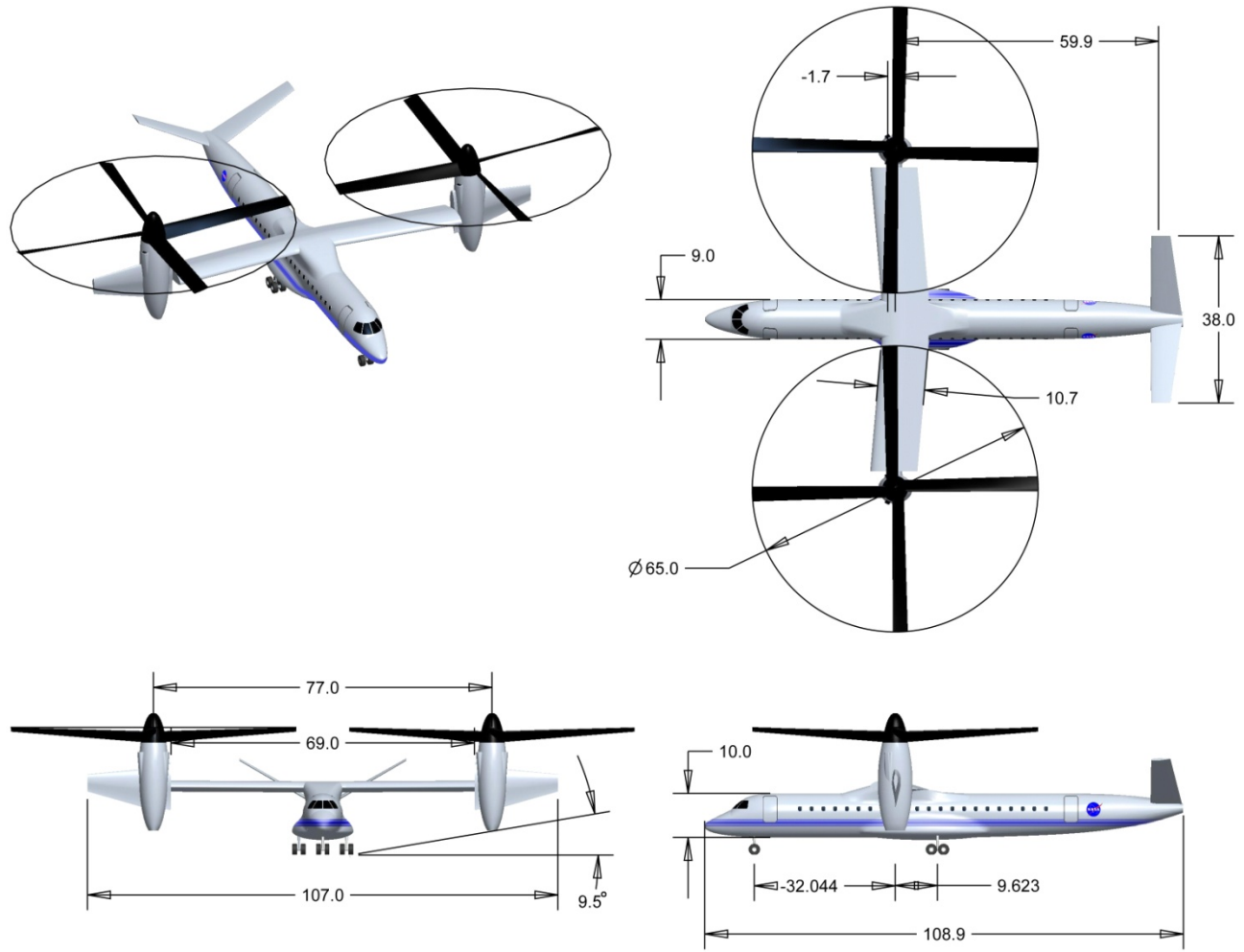


Fig. 1. The NASA Large Civil Tiltrotor, LCTR2 baseline version (dimensions in feet).

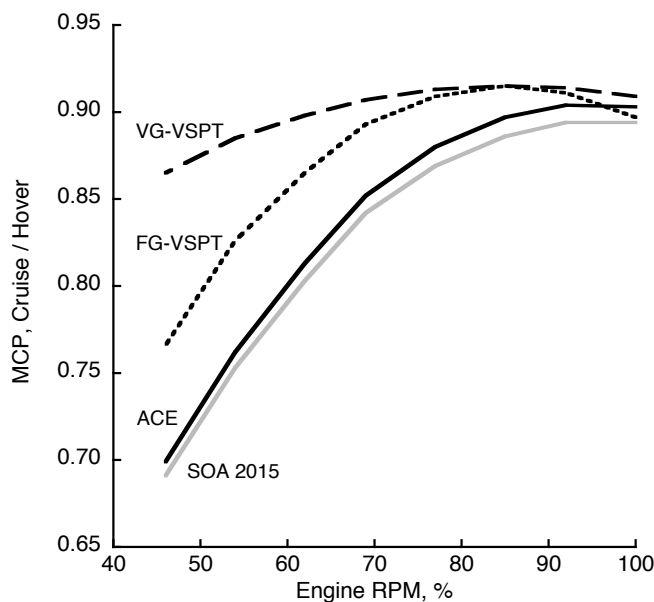


Fig. 2. Relative cruise to hover power versus engine rpm and power turbine type.

Rotor efficiency was determined by Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics (CAMRAD II, Refs. 8 and 9). Engine performance and weight, with and without VSPT technology, was estimated with the Numerical Propulsion System Simulation (NPSS, Ref. 10) and Weight Analysis of Turbine Engines (WATE, Ref. 11). NDARC integrates the rotor and engine performance models with a mission analysis to determine the minimum weight aircraft required to perform the specified mission. Gearbox design and weight are discussed in later sections.

As cruise altitude increases, density decreases, as does rotor profile power for a given rotor tip speed. Therefore, the optimum tip speed will tend to increase with altitude, but tip speed will be limited by either Mach effects or a rotor twist distribution too severe for adequate hover performance. Conversely, a very low tip speed will incur higher swirl losses. Rotor performance is further influenced by wing/rotor interaction, and wing efficiency is strongly affected by the rotor wake (Refs. 2 and 12; see also Ref. 13). CAMRAD II was used to analyze all of these effects using a

model with multiple wakes, with a wake for each rotor and the wing; performance was calculated for each combination of altitude and rotor tip speed. The CAMRAD II results were captured in algebraic rotor and wing performance models for efficient computation within NDARC.

NPSS was used to perform the gas turbine analyses. NPSS contains standard 0/1-D elements for the gas turbine components. These elements are configured into a representative steady-state, thermodynamic models using technology levels equivalent to LCTR2, with separate, but closely similar, models for the ACE and VSPT engine concepts. The engine state points over the expected operating profile, along with geometry and technology factors, are used to generate engine weights using WATE. These performance and weight analyses were converted to equivalent, algebraic engine models for NDARC.

Aircraft and Mission

Table 1 and Fig. 3 summarize the LCTR2 mission requirements. Only two changes were made since Ref. 2, both to the way the missions requirements were interpreted and modeled in NDARC. Category A OEI is modeled as occurring at 20 knots forward airspeed, which incorporates lessons from XV-15 flight tests (Refs. 14-16), and the climb to cruise altitude is modeled as two equal-height segments for better trim convergence during sizing.

Table 2 lists key constraints and assumptions imposed during the design. The three “minimum performance” constraints are the most important for sizing. In addition, the blade loading limit is a fallout of the 80-knot banked turn requirement (Table 1). The 80-knot turn represents an emergency maneuver and was analyzed in detail in Ref. 17,

which used CAMRAD II to derive the blade loading limit. The disk loading and wing loading were optimized in Ref. 18. The aircraft geometry, in particular fuselage diameter, wing span, and rotor radius, are set to provide acceptable passenger accommodations and to meet airport gate space limits. Hover tip speed is set by noise considerations.

Table 1. LCTR2 mission requirements.

Mission summary
Takeoff + 2 min hover OGE 5k ISA+20°C
Climb at V_{br} (credit distance to cruise segment)
Cruise at V_{br} for at least 1,000 nm range, 28k ISA
Descend at V_{br} (no range credit)
1 min hover OGE + landing, 5k ISA+20°C
Reserve (diversion): 100 nm V_{br} , 28k ISA
Reserve (emergency): 30 min V_{br} , 5k ISA+20°C
Operational requirements
One engine inoperative: Category A at 5k ISA+20°C
All-weather operations: CAT IIIC SNI, Free Flight
45-deg banked turn at 80 knots, 5k ISA+20°C, 90% MCP

An important set of constraints derives from the assumed aerodynamics technology, notably the rotor airfoils. For the present design study, the “virtual airfoils” described in Ref. 2 were used to represent an evolution of current airfoil performance. Rotor performance was predicted with CAMRAD II, based on the assumed performance of advanced airfoils, and included the effects of wing/rotor interference (Ref. 19). The process is described in Ref. 2 and is summarized here. The CAMRAD II results were represented within the NDARC rotor model as net values of rotor profile and induced drag, each varying with tip speed and altitude at the nominal cruise speed (300 knots).

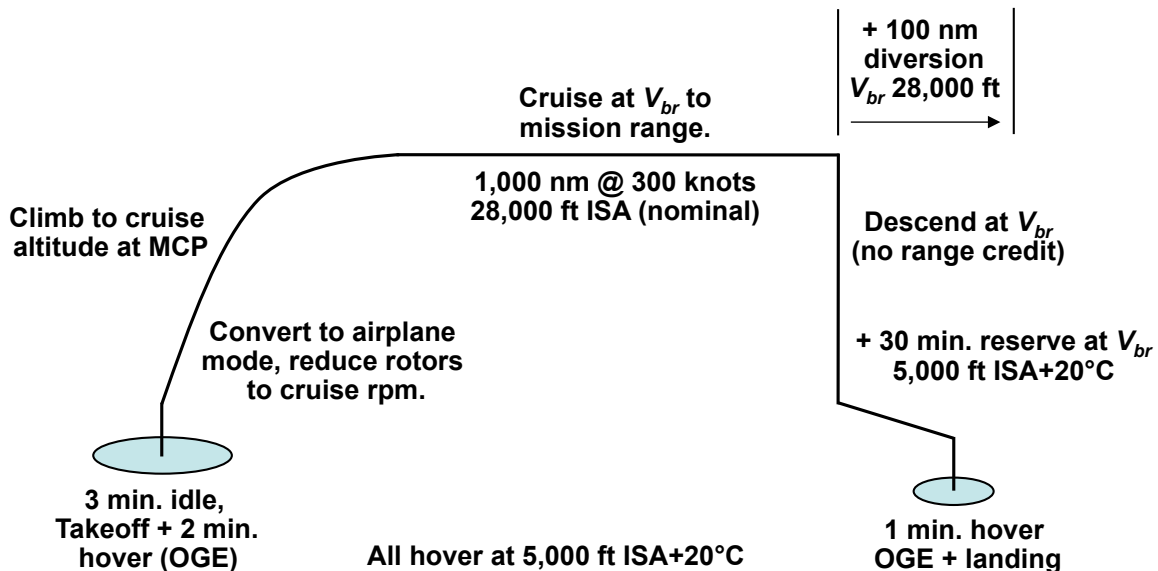


Fig. 3. LCTR2 nominal mission profile.

Optimum rotor twist depends upon cruise speed, hover conditions, and rotor tip speed, which may vary between hover and cruise. Here, the blade twist was always set to the classic helix twist angle. This is a very close approximation to the optimum twist distribution determined in Ref. 2. A small improvement in hover performance is possible with a revised twist distribution, but for a long-range aircraft, cruise efficiency is paramount and dominates the sizing process via fuel burn. Installed power is determined by OEI requirements. The blade loading and disk loading requirements (Table 2) also affect hover performance. While better hover performance is always useful, provided that it can be attained without compromising cruise efficiency, maximizing hover efficiency was not critical for this study. It was more informative to maintain strict equivalency in rotor performance while the propulsion model and other parameters were varied. A slight improvement in figure of merit would of course benefit all design variations, but would not materially change the comparative advantages of the engine/gearbox combinations studied here. A separate research effort is underway to develop fully optimized rotor aerodynamics, including airfoils, twist, taper, sweep, etc.

Table 2. LCTR2-03 design constraints for sizing.

Minimum Performance	
Max. takeoff weight at sea level standard, 100% MRP	
OEI at 5k ISA+20°C, 20 knots, 100% CRP	
Cruise speed 300 knots at 28k ISA, 90% MCP	
Design Constraint	
Payload (90 pax), lb	19,800
Cruise speed (90% MCP), knots	300
Fuselage diameter, ft	9.0
Length, ft	108.9
Wing span, ft	107.0
Wing sweep	-5.0 deg
Rotor radius, ft (max)	32.5
Rotor separation, ft	77.0
Number of blades	4
Precone, deg	6.0
Key Technology Assumptions	
Wing loading, lb/ft ²	105
Disk loading, lb/ft ²	14
^a Hover blade loading C_W/σ	0.151
^b Cruise SFC, lb/hr/hp	0.3255
^c Tip speed, hover, ft/sec	650

^aSet by maneuver requirement

^bAdvanced Conventional Engine spec.

^cSet by assumed future noise requirements

LCTR2 Design Evolution

The LCTR2 has evolved over time into three variants, reflecting evolving design processes along with updated technology assumptions. LCTR2-01 was designed with the RC sizing code, described in Ref. 20. The -02 variant was sized with NDARC using a revised mission model, an improved rotor performance model, and other refinements, as described in Ref. 2. The present variant, LCTR2-03, was resized using optimized wing and disk loadings from Ref. 18, and incorporates further refinements to the mission model, notably a change of OEI condition from hover to 20 knots. See the Appendix for details of the OEI specification.

Table 3 presents snapshots of the progress of the LCTR2 design evolution. The “2015” engine represents the state of engine technology projected in 2005 by the NASA Heavy Lift Rotorcraft Systems Investigation (Ref. 1) for an entry into service (EIS) date of 2015, and has been the baseline engine for LCTR2 since inception. Reference 1 assumed an aggressive technology push that in the event was not undertaken. At the risk of oversimplification, it could be said that either the weight or SFC goals of that engine are largely within reach with present technologies, but not both together without sacrificing engine life and maintainability. The ACE engine assumes technology available in 2035, and is discussed in detail in Refs. 21 and 22. With a major technology effort, EIS could conceivably be advanced to 2025. The designs summarized in Table 3 assume a nominal cruise tip speed of 350 ft/sec. Only major component weights are explicitly listed in Table 3; weight empty includes fixed weights, notably avionics, and all subsystem weights, such as flight controls.

The first column in Table 3, “hover”, represents the initial resizing with the optimized values of wing and disk loading from Ref. 18, and with the OEI condition taken at hover. The “20 knots” column, also for the 2015 engine, changes only the OEI condition from hover to 20 knots, as described in the Appendix. The “ACE” column changes only the assumed engine technology. The results for the 2015 engine reflect a modest reduction in gross weight compared to the LCTR2-02 variant (Ref. 2), but violate the 65-ft rotor diameter limit. Resizing with the ACE engine results in an aircraft that meets the diameter limit, with a reduction in gross weight of exactly (and coincidentally) 10%. All results in Table 3 and following include minor revisions and updates included in the latest version of NDARC (Release 1.5).

Table 3. LCTR2-03 design evolution for the baseline mission (Table 2).

Engine:	2015	2015	ACE
OEI Requirement:	Hover	20 knots	20 knots
Gross weight, lb	100,616	98,341	88,512
Weight empty, lb	65,660	63,865	57,728
Rotor weight, lb (both rotors)	8,146	7,910	6,911
Wing weight, lb (zero fuel)	8,776	8,568	7,888
Engines and drive train, lb	14,433	13,658	11,510
^a Fuselage empty weight, lb	12,593	12,378	11,434
Mission fuel, lb	13,695	13,228	9,528
Engine power, hp (MRP)	4×6,406	4×6,017	4×5,310
^b Rotor solidity	0.115	0.115	0.115
Rotor radius, ft	33.8	33.4	31.7
^c Hover C_T/σ	0.162	0.162	0.159
Cruise C_T/σ	0.0676	0.0672	0.0618
^d Wing area, ft ²	958	936	843
Drag D/q , ft ²	34.4	33.8	31.4

^aincludes landing gear; ^bthrust weighted; ^cstart of mission; ^dincludes extensions

Performance Models

The rotor performance model is summarized by Fig. 4 for the example of 30,000-ft cruise altitude. CAMRAD II was used to predict rotor performance in hover and cruise for each combination of cruise altitude and tip speed; hover tip speed was always 650 ft/sec, per Table 2. A prescribed-wake model was used for all cruise calculations; the wake model included separate wakes for each rotor and the wing. Rotor and wing performance calculations included full wing/rotor interference effects. A free-wake model was used for hover. The results were input into NDARC as equivalent rotor profile drag coefficient c_{do} , induced velocity ratio κ , and for the wing, Oswald efficiency factor e . Rotor twist was always set to the classic helix twist angle appropriate for the given cruise V_{tip} at 300 knots vehicle airspeed, hence hover performance includes the penalty of non-optimal twist at hover $V_{tip} = 650$ ft/sec.

Figure 4 displays the rotor performance model in terms of cruise propulsive efficiency (η_p) and figure of merit (FM). LCTR2's cruise-optimized rotor has a high cruise efficiency, at the cost of modest FM, although FM could be slightly improved as mentioned earlier. Note that η_p has a stronger peak than FM, although neither is strongly sensitive to cruise tip speed near peak efficiency.

Figure 5 displays the wing performance model as Oswald efficiency factor e . At lower values of V_{tip} , e can be greater than one because of beneficial wing/rotor interference (Ref. 12). As traditionally calculated, e can also be greater than one because the rotor wake slightly increases local dynamic pressure above the free-stream value.

The engines analyzed in this study—ACE and VSPT—are both assumed to have the same two-spool core, with a free-shaft power turbine to extract power for the rotor drive train. The assumed technology level allows an overall pressure ratio around 40 and maximum combustor exit temperature of at least 3000°F. See Refs. 21 and 22 for further discussion of cycle development and design details. The ACE engine has a two-stage power turbine, and the VSPT engine adds two additional stages to the power turbine to achieve a wide operating speed range with acceptable efficiency.

Gas turbine engines tend to run optimally over a fairly narrow range of rotational speeds and corrected flow conditions. Aerodynamically, this results in fairly constant ratios of velocities and angles between the engine flow and the rotating turbomachinery during typical engine operation. Turbomachinery designs have been further optimized for these conditions to achieve higher efficiency with fewer stages and less weight, with some efficiency penalty for off-design operation. The variable speed power turbine (VSPT) enables efficient operation over a larger range of turbomachinery speeds. To minimize the efficiency penalty for such operation, the VSPT design reduces the turbine loading by increasing the blade area and adjusting blade shape to efficiently accommodate the variation in flow speeds and relative angles (see Ref. 23 for detailed discussion). For the LCTR2 VSPT, this design requirement results in the power turbine going from two stages for the conventional power turbine (ACE) to four stages for FG-VSPT (fixed geometry). Having four stages for the FG-VSPT keeps efficiency approximately constant over the speed range. A three-stage FG-VSPT design was also reviewed, but had an unacceptable range of VSPT exit flow angles and efficiency losses over the desired range of

rotational speeds. The standard power turbine is about 15% of the total engine weight; so the additional stages of the VSPT doubles the power turbine weight, resulting in total engine weight increasing about 20%.

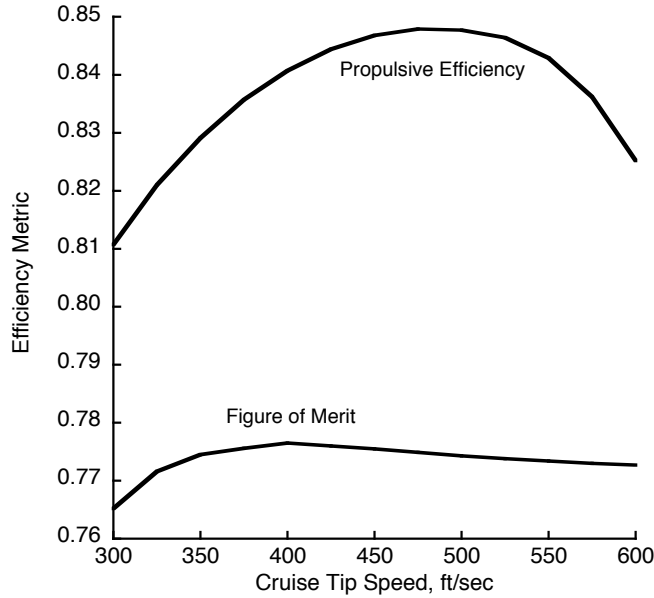


Fig. 4 Rotor performance versus tip speed; η_p is at 30,000 ft, 300 knots and includes wing/rotor interference; FM is at 5,000 ft ISA + 20°C.

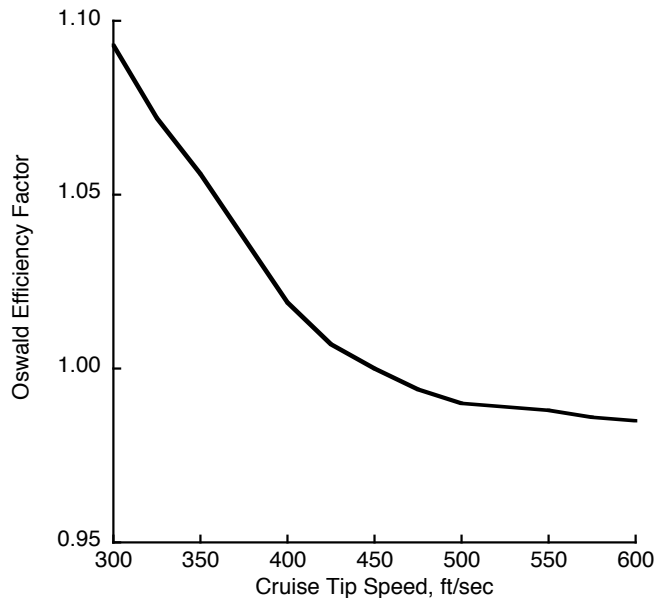


Fig. 5. Wing performance versus tip speed, calculated at 30,000 ft, 300 knots with full wing/rotor interference.

The differences between the ACE and VSPT engines can be summarized in terms of efficiency ratio, normalized to peak efficiency at hover tip speed (Fig. 6). Engine shaft speed is here converted to equivalent rotor tip speed for ease of comparison with the rotor and wing performance plots (Figs. 4-5). Power turbine efficiency η_t underlies the engine performance model in NDARC. η_t varies nonlinearly with engine shaft speed, hence with rotor tip speed. The NDARC engine model corrects for flight speed and altitude, including classic referred engine parameters, Mach number effects, ram air recovery factor, etc.

The conventional engine (ACE) suffers severe efficiency loss at low cruise tip speeds, and therefore requires a two-speed gearbox to keep the engine shaft speed near peak efficiency. The VSPT engine has negligible loss down to about 70% hover V_{tip} , and is still much more efficient than the conventional engine at $V_{tip} = 300$ ft/sec (power turbine efficiency ratio of 0.94 versus 0.78). Figures 7 and 8 show the power available and SFC for the two engines, as modeled in NDARC at the nominal 28,000-ft, 300-knot cruise condition. Figures 6-8 illustrate why the ACE concept must use a two-speed gearbox to avoid the performance loss at low rotor tip speeds.

The drive train utilizes a pair of compound planetary gearboxes, one for each rotor. The two-speed version adds a speed changing module at each input. Each speed changing module is a conventional clutched planetary gearbox (conventional, that is, for anything except rotorcraft). See Ref. 4 for details, including shift strategy. Reference 20 provides further information about the propulsion system studies upon which this paper relies.

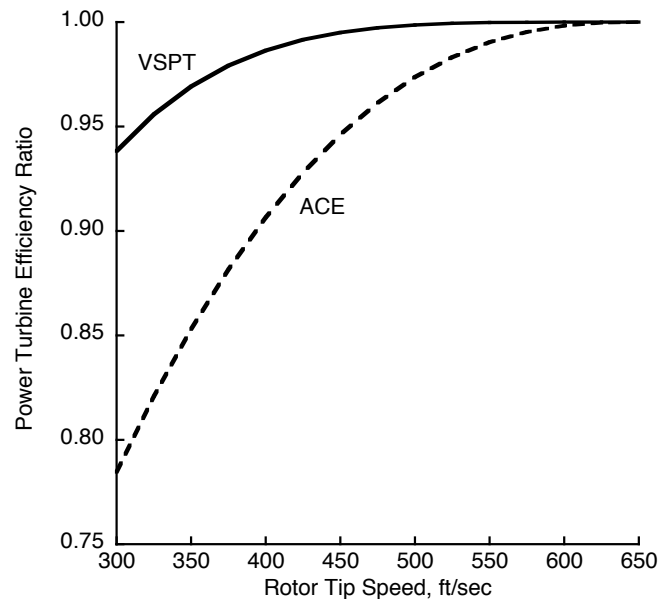


Fig. 6. NDARC power turbine efficiency model, normalized to hover.

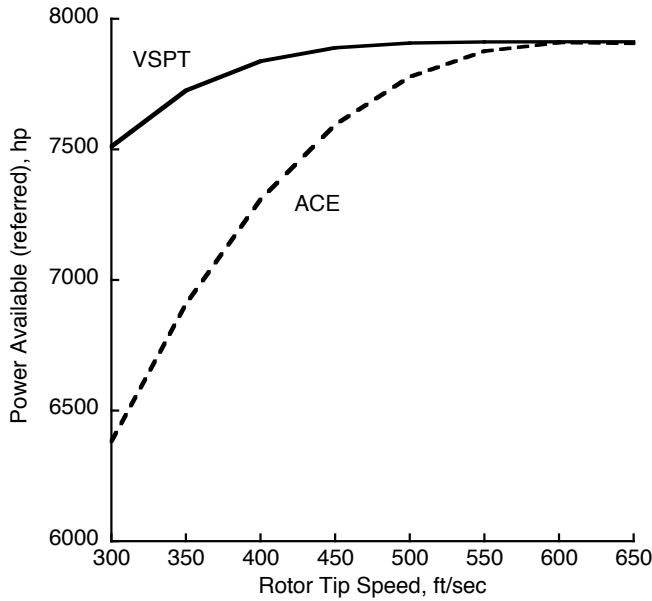


Fig. 7. Referred engine power available at 28,000 ft, 300 knots (NDARC engine model).

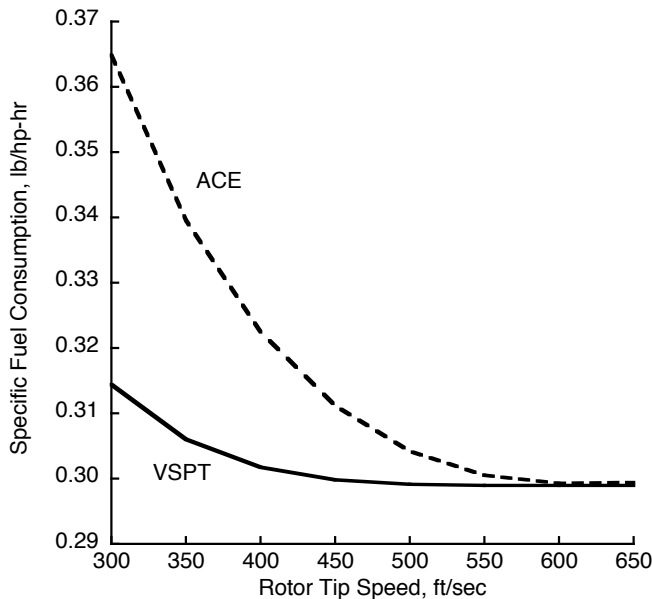


Fig. 8. Engine specific fuel consumption at 28,000 ft, 300 knots (NDARC engine model).

Aircraft Sizing Comparisons

Figures 9-12 summarize the sizing results based on the component performance models described above. Weight empty and mission fuel burn are plotted against cruise tip speed at several different cruise altitudes for the ACE and VSPT propulsion systems, each under two different interpretations of OEI requirements: hover and low-speed (20 knots). Takeoff power and rotor radius closely track weight empty and are accordingly not shown.

The results are very consistent: weight, fuel and power are all minimized at 30,000-ft cruise altitude. LCTR2 is capable of even higher cruise altitude, but the rotor efficiency declines sharply above 30,000 ft, severely so at high tip speeds, because of increasing tip Mach number. Replacing the OEI sizing condition at hover with that at 20 knots yields a substantial decrease in both weight empty and fuel burn.

The optimum cruise tip speed is independent of cruise altitude, very weakly dependent upon the engine/gearbox combination, but noticeably dependent upon the OEI condition. For the 20-knot OEI condition, the minimum weight empty is always at $V_{tip} = 300$ ft/sec, whereas for the hover OEI condition, the optimum V_{tip} is in the range 350-400 ft/sec, depending on the engine. The VSPT engine yielded lower gross weight and mission fuel at all but the lowest tip speeds.

However, most trends for hover OEI are nearly flat at the optimum tip speed. Small changes in technology assumptions or modeling could easily shift the optimum tip speed higher or lower. It is therefore not surprising that the optimal tip speed for hover OEI is slightly lower than that found in Ref. 2. Note also that the rotor was always given the classic helical twist distribution, which would slightly favor 20-knot OEI over hover OEI. The LCTR2 rotor design has scope for further refinement of twist in favor of hover (or very low speed), which could also affect the optimum cruise tip speed.

Figures 9-12 would seem to imply that lower cruise tip speeds and higher cruise altitudes than shown would be beneficial. However, gearbox weight and engine efficiency will eventually limit the lowest acceptable tip speed. The effect of declining power turbine efficiency for the VSPT engine can be seen in Fig. 9 for the hover OEI condition, where weight empty and fuel burn begin to increase at the lowest tip speed for the VSPT engine, consistent with Figs. 6-8. Furthermore, all calculations were based upon the same set of rotor airfoils. Different thickness and camber distributions would presumably result in different tradeoffs between hover and cruise performance, and therefore yield different optimum cruise tip speeds. The ACE and VSPT concepts would likely both benefit from different rotor airfoils, which greatly broadens the LCTR2 design space and its associated challenges. A separate research effort is underway to refine the rotor aerodynamics, including but not limited to new airfoils.

The minimum weight solution is necessarily a compromise between maximum component efficiency (η_t , η_p , FM, and e) and maximum aircraft efficiency, here represented as total aircraft lift-to-drag ratio L/D_e . Minimum weight empty never occurs at the cruise tip speed for peak η_p (Fig. 4), and only rarely at the tip speed for peak FM (Fig. 5). η_t , η_p , FM, and e are all dimensionless metrics and do not in themselves include any weight penalties, nor do they

directly reflect airframe drag. The drag penalty is implied by Fig. 13, which plots L/D_e in cruise against rotor tip speed. Note that $L/D_e = WV/P$. The trends of both weight empty and fuel burn are generally upward with tip speed, consistently so above about 400 ft/sec (Figs. 9-12). The

strong downward trend in L/D_e with V_{tip} must therefore be caused by rapidly increasing drag. The downward trends in e and L/D_e shift the minimum weight solution to a lower tip speed than that for peak η_t , η_p , or FM.

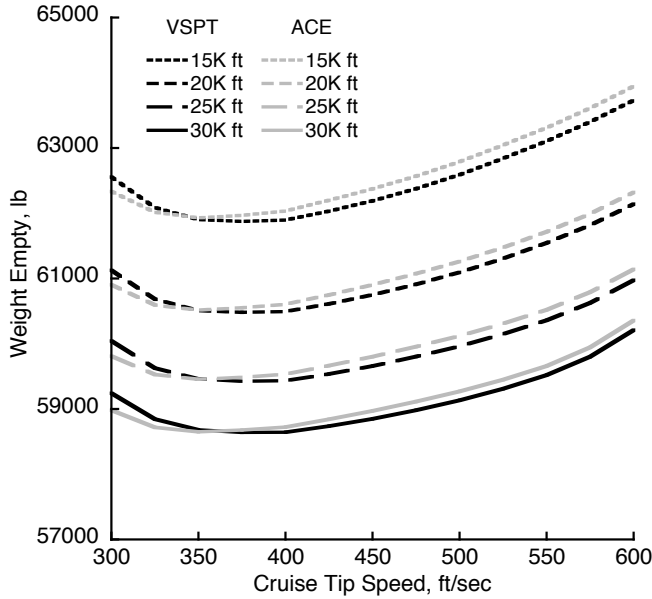


Fig. 9. Weight empty versus rotor tip speed for two propulsion concepts, for the hover OEI sizing condition.

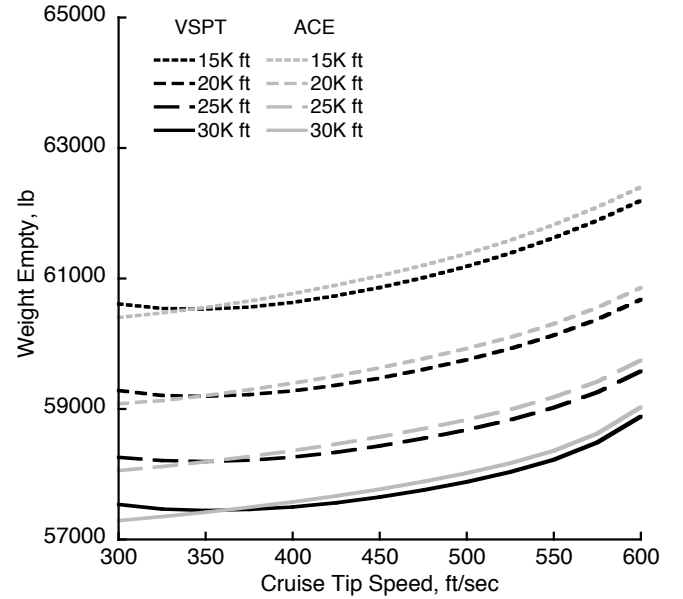


Fig. 11. Weight empty versus rotor tip speed for two propulsion concepts, for the 20-knot OEI sizing condition.

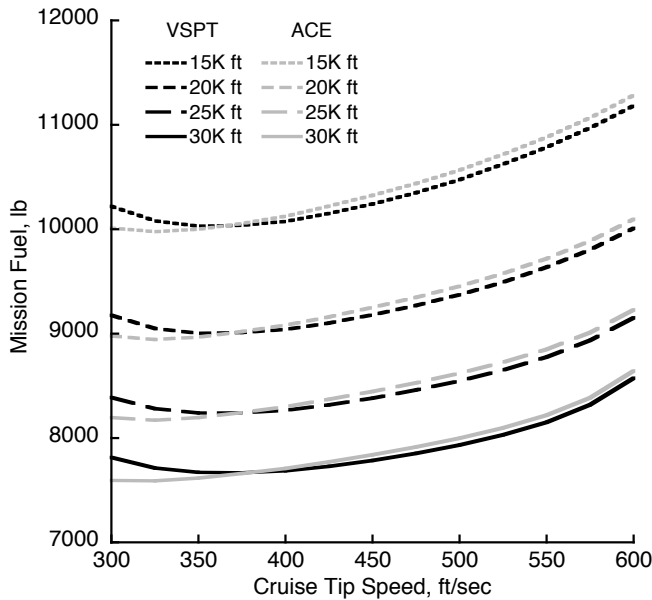


Fig. 10. Mission fuel burn versus rotor tip speed for two propulsion concepts, for the hover OEI sizing condition.

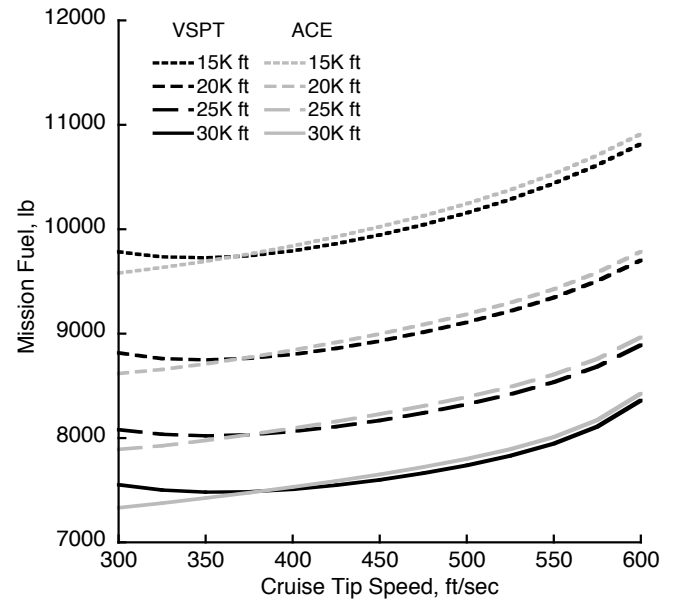


Fig. 12. Mission fuel burn versus rotor tip speed for two propulsion concepts, for the 20-knot OEI sizing condition.

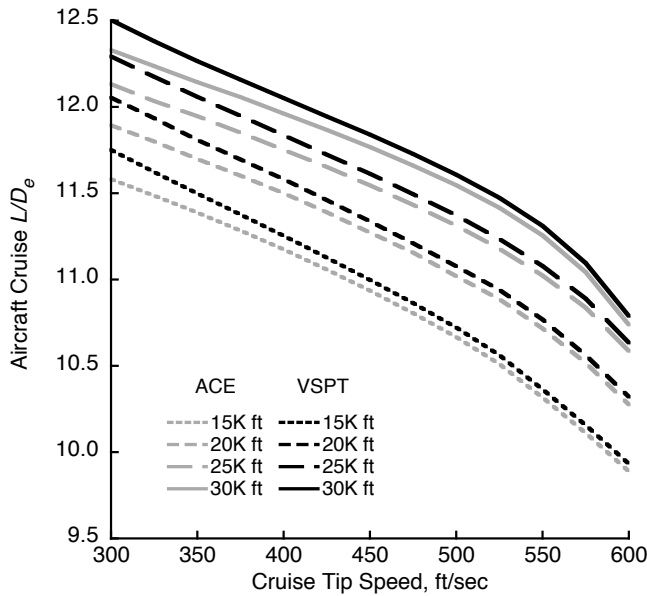


Fig. 13. Aircraft L/D_e versus rotor cruise tip speed for the 20-kt OEI sizing condition.

Table 4. Re-sized LCTR2 for two different propulsion concepts.

Propulsion Concept:	ACE	FG-VSPT
OEI requirement	20 knots	20 knots
Gross weight, lb	87,936	88,019
Weight empty, lb	57,420	57,441
Rotor weight, lb (both rotors)	6,854	6,862
Wing weight, lb (zero fuel)	7,855	7,855
Engines, lb	2,644	3,044
Drive train, lb	7,467	6,908
^a Fuselage empty weight, lb	11,378	11,386
Fuel burn, lb	7,423	7,479
Engine power, hp (MRP)	4×5,287	4×5,292
^b Rotor solidity	0.115	0.115
Rotor radius, ft	31.6	31.6
^c Hover C_T/σ	0.159	0.159
Cruise C_T/σ	0.0660	0.0652
^d Wing area, ft ²	838	838
Drag D/q , ft ²	31.3	31.0
Rotor cruise tip speed, ft/sec	300	350
^e Max speed at 30K ft, knots	328	352
^e Service ceiling, ft	37,931	39,518
^e Hover ceiling (HOGE), ft	6,427	6,426

^aincludes landing gear

^bthrust weighted

^cstart of mission

^dincludes extensions

^e100% MCP

Table 4 summarizes the differences between the two propulsion system concepts for the LCTR2, here sized at the optimum cruise tip speed and altitude for each concept, and always applying the 20-knot OEI condition. The vehicle and component weights are less than 0.1% different, except for the propulsion system, where the ACE version is 1.6% heavier than the VSPT. The differences in power and drag are also less than 1%. On the other hand, the VSPT consumes 1% more fuel, hence its vehicle gross weight is slightly heavier. The VSPT has both higher maximum speed and maximum ceiling, but the latter value should be taken with caution because the LCTR2 was not designed for such altitudes, nor is the performance model well established for those conditions. Changing the OEI requirement to hover increases installed power by 5.6%, mission fuel burn by 2.6%, and weight empty by 2.1%; the percentage increases are the same for the ACE and VSPT.

Gearbox Weight Sensitivity

Given the small differences between the resized LCTR2 for the two propulsion concepts, ACE versus VSPT, it is appropriate to examine the impact of the technology assumptions for the two engines. Both engines were designed with equivalent turbine technology, with the key difference being that the VSPT has two extra stages to achieve a wider operating speed band. This design approached yielded nearly identical reference SFC values: 0.3250 for the VSPT, and 0.3255 for the ACE, both taken at nominal takeoff power at sea level standard conditions.

For aircraft sizing, the most important variable is then weight. The VSPT weight is modeled as a 20% factor over the ACE weight, determined by the number of turbine stages. The weight of the shifting module for the two-speed gearbox is modeled as a 10% penalty on gearbox weight; see Ref. 4 for a specific example.

Figures 14 and 15 summarize the results of varying the gearbox weight for the ACE propulsion concept. Weight trends are shown for the two most extreme tip speeds analyzed, 300 and 600 ft/sec (Figs. 14 and 15, respectively). The weight empty for the VSPT concept is plotted as a dot on each curve. The trends are closely similar at all altitudes for both cruise tip speeds, and shift vertically with tip speed. These results suggest that a 10% weight penalty for a shifting module is roughly equivalent to a 20% weight penalty for the VSPT. The weight empty trends would be expected to be about twice as sensitive to the VSPT turbine weight penalty.

For values on a weight penalty curve above that for the VSPT engine, the ACE engine will have a higher vehicle weight empty. For $V_{tip} = 300$ ft/sec, the intersection is just over 11%, and for $V_{tip} = 600$ ft/sec, the intersection is 9%.

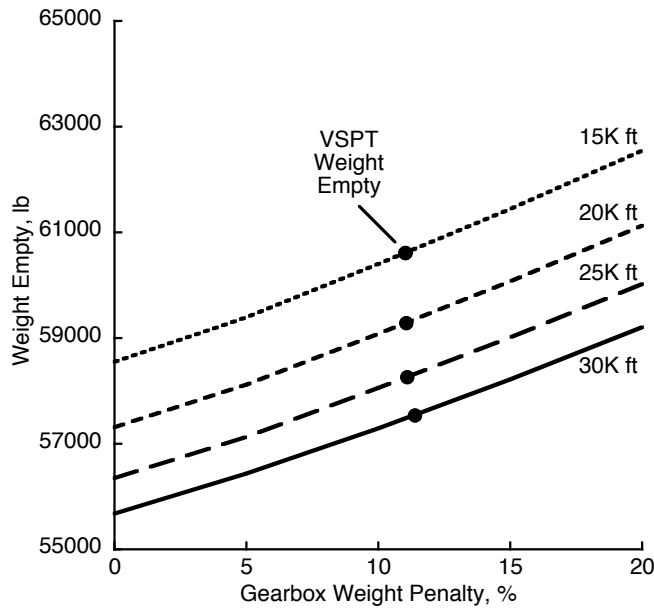


Fig. 14. Trends of weight empty with ACE gearbox weight penalty at $V_{tip} = 300$ ft/sec.

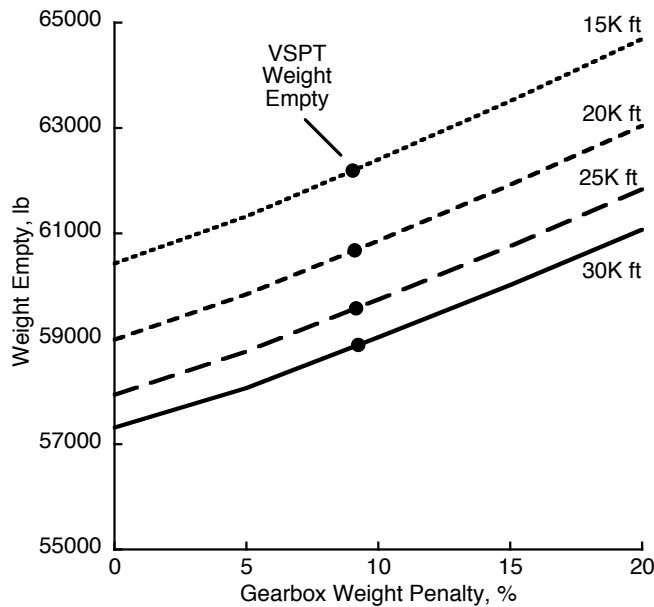


Fig. 15. Trends of weight empty with ACE gearbox weight penalty at $V_{tip} = 600$ ft/sec.

Effect of Mission Range

The LCTR2 was resized for different mission ranges for the two propulsion concepts, at cruise altitudes from 15,000 to 30,000 ft; the 20-knot OEI sizing condition was always applied. The results can be summarized in Figs. 16-17, which show the two most extreme ranges analyzed (500 nm and 1,500 nm) along with the nominal mission (1,000 nm).

The weight trends for both concepts were closely similar to those previously shown for the nominal mission range, with the 30,000-ft cruise altitude always having the lowest weight, fuel and power; the optimum cruise tip speed was always 300 ft/sec for the ACE concept and 350 ft/sec for VSPT. Weight empty and mission fuel burn are shown below for the optimum value of cruise V_{tip} for each propulsion concept. Engine power is also plotted (Fig. 18), simply to illustrate its close similarity to weight empty (Fig. 16). The differences between ACE and VSPT are negligible, compared to the effects of mission range.

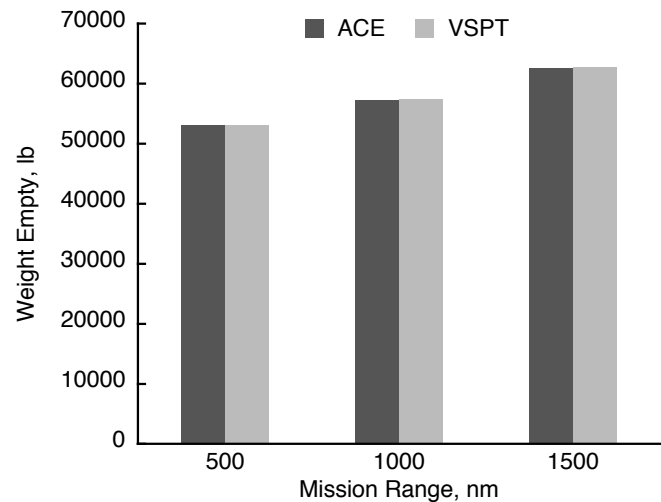


Fig. 16. Summary of effect of mission range on LCTR2 weight empty.

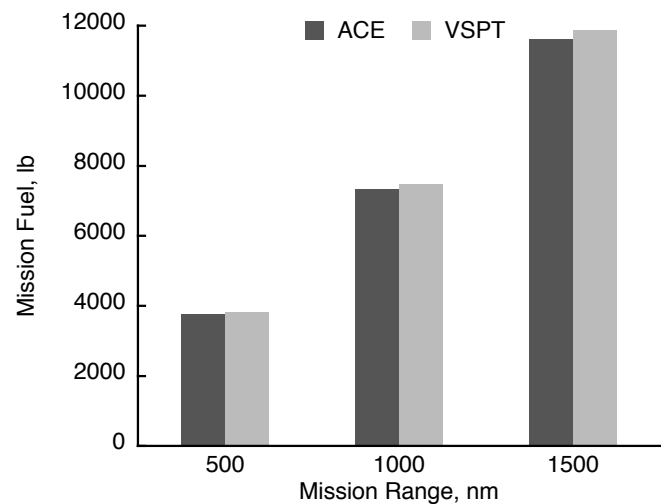


Fig. 17. Summary of effect of mission range on LCTR2 mission fuel burn.

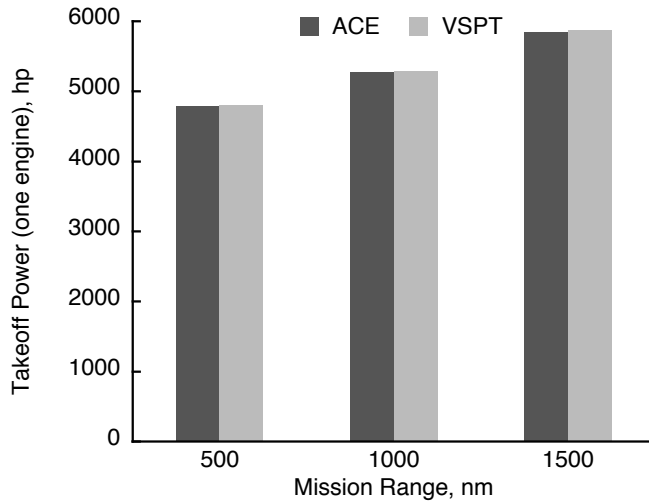


Fig. 18. Summary of effect of mission range on LCTR2 takeoff power required.

Conclusions

The Large Civil Tiltrotor (LCTR2) was sized with two different propulsion system concepts: an advanced conventional engine (ACE) with a two-speed gearbox, and a variable-speed power turbine engine (VSPT) with a fixed-ratio gearbox. Sizing was performed for rotor cruise tip speeds from 300 to 600 ft/sec at altitudes from 15,000 to 30,000 ft. Nominal mission range was 1,000 nm. The sizing analysis was therefore a tradeoff between engine weight and gearbox weight, varying with cruise tip speed and altitude. The analyses also compared two different OEI sizing criteria: OEI in hover and OEI at 20 knots.

The results were highly consistent: both engines yielded the lowest weight empty and fuel burn at 30,000 ft cruise altitude, and the 20-knot OEI criterion resulted in lower weight empty and fuel burn than the hover OEI criterion. The trends in engine power and rotor radius closely followed those for weight. A cruise tip speed of 350 ft/sec was optimal for the VSPT engine, whereas 300 ft/sec was optimal for the ACE, but the sized aircraft weights were less than 0.1% different. It is possible that even higher cruise altitudes or lower tip speeds would be beneficial, but analysis of such will require more refined component performance models.

Additional sizing analyses were performed at different mission ranges, from 500 to 1,500 nm, with remarkably similar results: the optimum altitude and cruise tip speed were the same for all ranges, with negligible variation in the relative merits of the two engine concepts. The working conclusion is that for a two-speed gearbox weight penalty of 11%, the ACE and VSPT concepts yield equivalent vehicle weight and power, with little evident dependence upon mission range or altitude.

In retrospect, this result is not surprising: both the VSPT engine and two-speed gearbox weight models have a simple percentage weight penalty over the lighter, more conventional variant. Therefore, the sizing trends should be linearly shifted with respect to each other. What was surprising was the extreme consistency with cruise tip speed, mission range, and altitude. A very slight nonlinear trend can be discerned in the plots of weight empty versus gearbox weight penalty (Figs. 14 and 15), but the trend is not likely to be significant, given the necessary simplifications of the rotor, wing and engine performance models. The obvious recommendation is to further refine the engine performance and gearbox weight models, in order to better define the tradeoffs between a VSPT engine and a two-speed gearbox.

Perhaps the most robust conclusions are that a 20-knot OEI sizing criterion resulted in lower vehicle weight and power, and shifted the optimum cruise tip speed to the lowest value analyzed for the ACE engine. For the VSPT engine, the 20-knot OEI criterion resulted in weight trends nearly insensitive to tip speed near the optimum value. These conclusions, however, are based upon the assumption that the download speed threshold is independent of disk loading, wing/rotor area ratio, and other scaling parameters for which little test data exist.

A mission altitude of 30,000 ft always yielded the lightest vehicle. The interpretation offered here is that the LCTR2 is overpowered for climb and cruise, therefore the rotors and engines can easily manage a rapid climb and high cruise altitude. However, the nominal rotor and wing designs were not intended for higher altitudes (or cruise speeds) than those examined here. LCTR2 could benefit from rotor and wing airfoils optimized for more extreme operating conditions; such an aerodynamic optimization effort is underway and merits encouragement.

The results suggest that the original baseline mission (28,000-ft cruise altitude, $V_{tip} = 350$ ft/sec) is close to the optimum and therefore remains a reasonable basis for comparison studies. The close similarity of results for ACE versus VSPT, combined with the low sensitivity to cruise tip speed near the optimum, imply that the choice of engine and drive train will depend upon other technology developments, such as better exploitation of wing/rotor interference.

An important question is whether any reasonable improvement in the weight and performance of the LCTR2 with a two-speed gearbox would be enough to persuade an operator to accept the maintenance costs and operational constraints of in-flight shifting versus the complexity and potentially increased maintenance of a VSPT. The economic tradeoffs are beyond the scope of this paper, but merit close study.

Appendix

The rationale for the 20-knot OEI condition derives from XV-15 flight test data, briefly discussed here. Figure A1 shows referred rotor power (one side) versus airspeed (Ref. 14); the nacelles are at 90 deg and the flaps set to 40 deg, which are the standard settings for XV-15 in hover and very low airspeed. The power bucket is between roughly 30 and 70 knots.

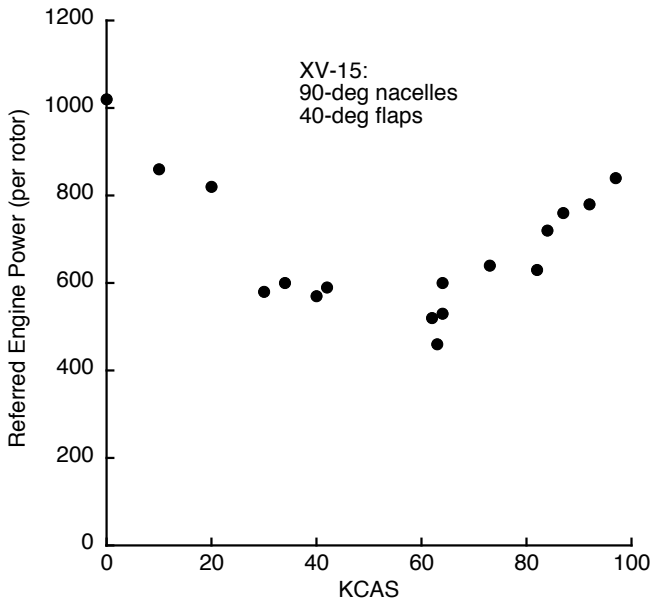


Fig. A1. XV-15 referred rotor power vs. airspeed in helicopter mode, with 40-deg flaps (Ref. 14).

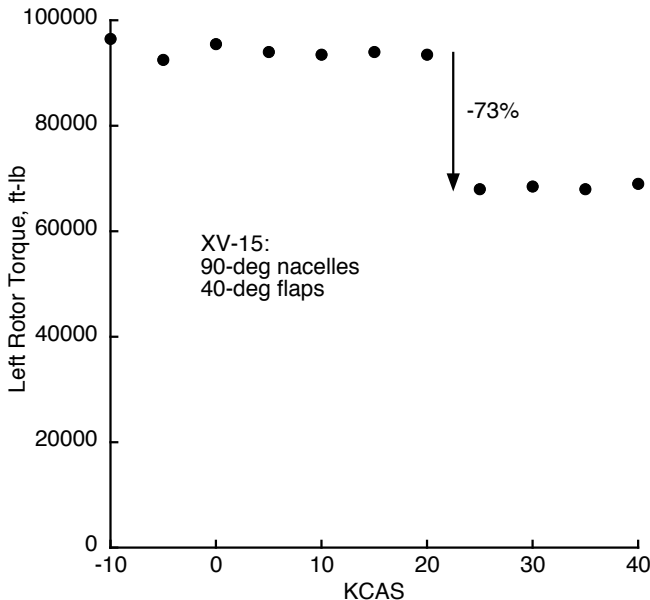


Fig. A2. XV-15 rotor shaft torque vs. airspeed in helicopter mode, with 40-deg flaps (Ref. 15).

Figure A2 shows more detail. Here, the Y-axis is left rotor torque, a more direct measurement than referred power, and the airspeed scale is compressed (Ref. 15). The references do not give details of atmospheric conditions or piloting technique, and the data were apparently taken at different times, so it is not surprising that the two figures do not match perfectly. The salient point is that there is a very sudden drop in torque as the airspeed exceeds 20 knots. Average torque above 20 knots is 73% less than the average value below 20 knots (Fig. A2).

In hover, the airflow along the wing is spanwise, turning into a fountain above the fuselage, with resulting high download. At sufficient forward airspeed, the flow shifts to chordwise and the fountain collapses, with a large decrease in download (Ref. 13). Figure A2 shows that this occurs at 20 knots for the XV-15.

The requirement for LCTR2 is safe operation in the event of an engine failure. Low speed in the immediate vicinity of an airport is the most critical condition. The LCTR2 can easily operate with a failed engine in airplane mode. If an engine fails in hover, the aircraft can simply settle back onto the landing pad. If, however, an engine fails while the LCTR2 is accelerating away from hover, it may not be possible to immediately return to the landing area: the aircraft must have sufficient performance to continue flight in the airport pattern until it can return to land.

XV-15 flight tests showed that 20 knots is an easily achievable flight condition and poses no difficulties for handling qualities. With the nacelles at 75 deg (15 deg forward tilt), a tiltrotor will accelerate at $\frac{1}{4} g$ and achieve 20 knots in just over 4 seconds. Furthermore, a 20-knot OEI criterion is arguably conservative. At low speeds, proprotors become more efficient with airspeed, hence a 40- or 50-knot OEI condition is achievable at the same power as 20 knots. Limiting the OEI sizing condition to 20 knots is the most restrictive criterion consistent with spanwise wing flow.

LCTR2 download is modeled as a vertical drag increment equivalent to 7% of gross weight in hover, representing advanced drag-reduction technology, with zero download at 20 knots and above.

Acknowledgments

The authors would like to thank Jason Slaby (Pennsylvania State University) for his assistance in updating the LCTR2 model to the latest version of NDARC. The authors would also like to thank Douglas Thurman (U. S. Army Research Laboratory, Glenn Research Center) for assistance on the engine performance models and generating the engine weights for the ACE and FG-VSPT engines, and Gerard Welch (NASA Glenn) for the FG-VSPT component performance map. The authors are, as always, deeply indebted to Wayne Johnson of NASA Ames Research Center for his insight, advice and assistance in all things regarding rotorcraft.

References

1. Johnson, W., Yamauchi, G. K., and Watts, M. E., "NASA Heavy Lift Rotorcraft Systems Investigation," NASA TP-2005-213467, September 2005.
2. Acree, C. W., "Integration of Aeromechanics Analysis with the Conceptual Design of a Large Civil Tiltrotor," AHS Aeromechanics Specialists' Conference, San Francisco, CA, January 2010.
3. Acree, C. W., Yeo, H., and Sinsay, J. D., "Performance Optimization of the NASA Large Civil Tiltrotor," International Powered Lift Conference, London, UK, July 2008; also NASA TM-2008-215359, June 2008.
4. Robuck, M., Wilkerson, J., Zhang, Y., Snyder, C. A., and Vonderwell, D., "Design Study of Propulsion and Drive Systems for the Large Civil TiltRotor (LCTR2) Rotorcraft," AHS 67th Annual Forum Proceedings, Virginia Beach, VA, May 2011.
5. Johnson, W., "NDARC, NASA Design and Analysis of Rotorcraft," NASA TP 2009-215402, December 2009.
6. Johnson, W., "NDARC—NASA Design and Analysis of Rotorcraft: Theoretical Basis and Architecture," AHS Aeromechanics Specialists' Conference, San Francisco, CA, January 2010.
7. Johnson, W., "NDARC—NASA Design and Analysis of Rotorcraft: Validation and Demonstration," AHS Aeromechanics Specialists' Conference, San Francisco, CA, January 2010.
8. Johnson, W., "Rotorcraft Aerodynamics Models for a Comprehensive Analysis," AHS 54th Annual Forum Proceedings, Washington, D.C., 1998.
9. Johnson, W., "CAMRAD II Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics," Johnson Aeronautics, Palo Alto, CA, 2005.
10. Jones, S. M., "An Introduction to Thermodynamic Performance Analysis of Aircraft Gas Turbine Engine Cycles Using the Numerical Propulsion System Simulation Code," NASA/TM-2007-214690, March 2007.
11. Tong, M.T. and Naylor, B.A., "An Object-Oriented Computer Code for Aircraft Engine Weight Estimation," GT2008-50062, ASME Turbo-Expo 2008, Berlin, Germany, June 2008.
12. Kroo, I., "Propeller-Wing Integration for Minimum Induced Loss," *Journal of Aircraft*, Vol. 23, No. 7, July 1986.
13. McVeigh, M. A., Grauer, W. K., and Paisley, D. J., "Rotor/Airframe Interactions on Tiltrotor Aircraft," AHS 44th Annual Forum Proceedings, Washington, D.C., June 1988.
14. Schillings, J. J., Roberts, B. J., Wood, T. L., and Wernicke, K. G., "Maneuver Performance of Tiltrotor Aircraft," AHS 43rd Annual Forum Proceedings, St. Louis, MO, May 1987 (Rev. June 1987).
15. McEntire, K., "XV-15 Full Scale Test Data Correlation Report," Bell report 901-909-003, November 1985.
16. Arrington, W. L., Kumpel, M., Marr, R. L., and McEntire, K. G., "XV-15 Tilt Rotor Research Aircraft Flight Test Data Report, Vol. II," NASA CR-177406, USAAVSCOM TR-86-A-1, June 1985.
17. Yeo, H., Sinsay, J. D., and Acree, C. W., "Blade Loading Criteria for Heavy Lift Tiltrotor Design," AHS Southwest Region Technical Specialists' Meeting on Next Generation Vertical Lift Technologies, Dallas, TX, October 2008.
18. Russell, C. and Johnson, W., "Conceptual Design and Mission Selection for a Large Civil Compound Helicopter," AHS Future Vertical Lift Aircraft Design Conference, San Francisco, CA, January 2012.
19. Yeo, H. and Johnson, W., "Performance and Design Investigation of Heavy Lift Tiltrotor with Aerodynamic Interference Effects," AHS 63rd Annual Forum Proceedings, Virginia Beach, VA, May 2007.
20. Preston, J. and Peyran, R., "Linking a Solid-Modeling Capability with a Conceptual Rotorcraft Sizing Code," AHS Vertical Lift Aircraft Design Conference, San Francisco, CA, January 2000.
21. Snyder, C. A. and Thurman, D. R., "Effects of Gas Turbine Component Performance on Engine and Rotary Wing Vehicle Size and Performance," AHS 66th Annual Forum Proceedings, Phoenix, AZ, May 2010.
22. Snyder, C. A., "Defining Gas Turbine Engine Performance Requirements for the Large Civil Tiltrotor (LCTR2)," AHS 67th Annual Forum Proceedings, Virginia Beach, VA, May 2011.
23. Welch, G. E., "Computational Assessment of the Aerodynamic Performance of a Variable-Speed Power Turbine for Large Civil Tilt-Rotor Application," AHS 67th Annual Forum Proceedings, Virginia Beach, VA, May 2011, NASA TM-2011-217124.