Preliminary Assessment of Variable Speed Power Turbine Technology on Civil Tiltrotor Size and Performance

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Abstract

A Large Civil Tiltrotor (LCTR) conceptual design 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 capability. This paper performs a preliminary assessment of variable-speed power turbine technology on LCTR2 sizing, while maintaining the same, advanced technology engine core. Six concepts were studied; an advanced, single-speed engine with a conventional power turbine layout (Advanced Conventional Engine, or ACE) using a multi-speed (shifting) gearbox. There were five variable-speed power turbine (VSPT) engine concepts, comprising a matrix of either three or four turbine stages, and fixed or variable guide vanes; plus a minimum weight, two-stage, fixed-geometry VSPT. The ACE is the lightest engine, but requires a multi-speed (shifting) gearbox to maximize its fuel efficiency, whereas the VSPT concepts use 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 gross and empty weight, propulsion system weight and mission fuel burn for the civil mission. 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. Major study assumptions are presented and discussed. Impressive engine power-to-weight and fuel efficiency reduced vehicle sensitivity to propulsion system choice. The 10% weight penalty for multi-speed gearbox was more significant than most engine technology weight penalties to the vehicle design because drive system weight is more than two times engine weight. Based on study assumptions, fixed-geometry VSPT concept options performed better than their variable-geometry counterparts. Optimum design gross weights varied 1% or less and empty weights less than 2% among the concepts studied, while optimum fuel burns varied up to 5%. The outcome for some optimum configurations was so unexpected as to recommend a deeper look at the underlying technology assumptions.

Notation

A	rotor disk area
c_{do}	section profile drag coefficient
C_T	rotor thrust coefficient, $T/(\rho A V_{tip}^2)$
C_W	rotor weight coefficient, $W/(\rho A V_{tip}^2)$
D	drag
e	span efficiency factor
FM	rotor hover figure of merit, $T(\sqrt{T/2\rho A})/P$
L	lift
L/D_e	aircraft lift over equivalent drag, WV/P
P	power required
q	dynamic pressure
T	rotor thrust
V	airspeed
V_{br}	aircraft best-range speed
V_{tip}	rotor tip speed
W	gross weight
WE	empty weight
η_p	propulsive efficiency, TV/P
η_t	power turbine efficiency
κ	induced velocity factor
ρ	air density
σ	rotor solidity (thrust-weighted)
ACE	Advanced Conventional Engine
CAMRAD	Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics
CRP	Contingency Rated Power

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EIS	Entry Into Service
HOGE	Hover Out of Ground Effect
ISA	International Standard Atmosphere
LCTR2	Large Civil Tilt Rotor—iteration 2
MCP	Maximum Continuous Power
MRP	Maximum Rated Power (take-off power)
NDARC	NASA Design and Analysis of Rotorcraft
NPSS	Numerical Propulsion System Simulation
OEI	One Engine Inoperative
OGE	Out of Ground Effect
SFC	Specific Fuel Consumption, lb/hr-HP
SLS	Sea Level Static
SNI	Simultaneous Non-Interfering approach
VSPT	Variable Speed Power Turbine engine: FG: fixed geometry VG: variable geometry
WATE	Weight Analysis of Turbine Engines

Introduction

The Large Civil Tiltrotor (LCTR) conceptual design 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 capability. 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 performs a preliminary assessment of the impact of advanced engine and gearbox concepts on mission performance, and presents criteria 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; cruise tip speed can be as low as 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 key design 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 requirements.

The motivation of this paper was to explore the implications of the rotor/engine/gearbox tradeoff with expected advances in engine technology. This paper extends the work of Ref. 4 to include a wider variety of engine configurations. It was expected that the result would indicate a clear choice between propulsion concepts (standard or various types of VSPT vs. multi-speed gearbox, and fixed vs. variable geometry), but as will be shown, the outcome was so unexpected as to recommend a deeper look at the underlying technology assumptions. Additional performance requirements were also uncovered during the study that could change and add to design requirements. These requirements could change technology and performance assumptions and study conclusions. Therefore, subsequent effort is warranted and will be discussed.

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 a conventional power turbine layout (Advanced Conventional Engine, or ACE); and two concepts using variable-speed power turbine (VSPT) technology (Ref. 5). VSPT technology includes a design methodology that sacrifices some maximum efficiency, adds some additional weight and possibly increases complexity (using variable geometry, normally by employing variable guide vanes) to extend the range of power turbine (and therefore rotor) rpm while maintaining high efficiency and work potential in the power turbine. Initial engine options explored in Ref. 5 included a variable geometry VSPT (VG-VSPT) to maximize power turbine rpm variability while maintaining efficiency and operability, but also incurring a significant weight and complexity penalty. Based on those penalties, a more conventional, fixed-geometry VSPT (FG-VSPT) concept was later included. Study results (Ref. 5) indicated 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 and fuel burn.

A recent NASA study (Ref. 4) revisited the engine with a standard power turbine and two-speed gearbox versus FG-VSPT engine with fixed-ratio gearbox concepts while varying mission cruise altitude and OEI requirements. 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.

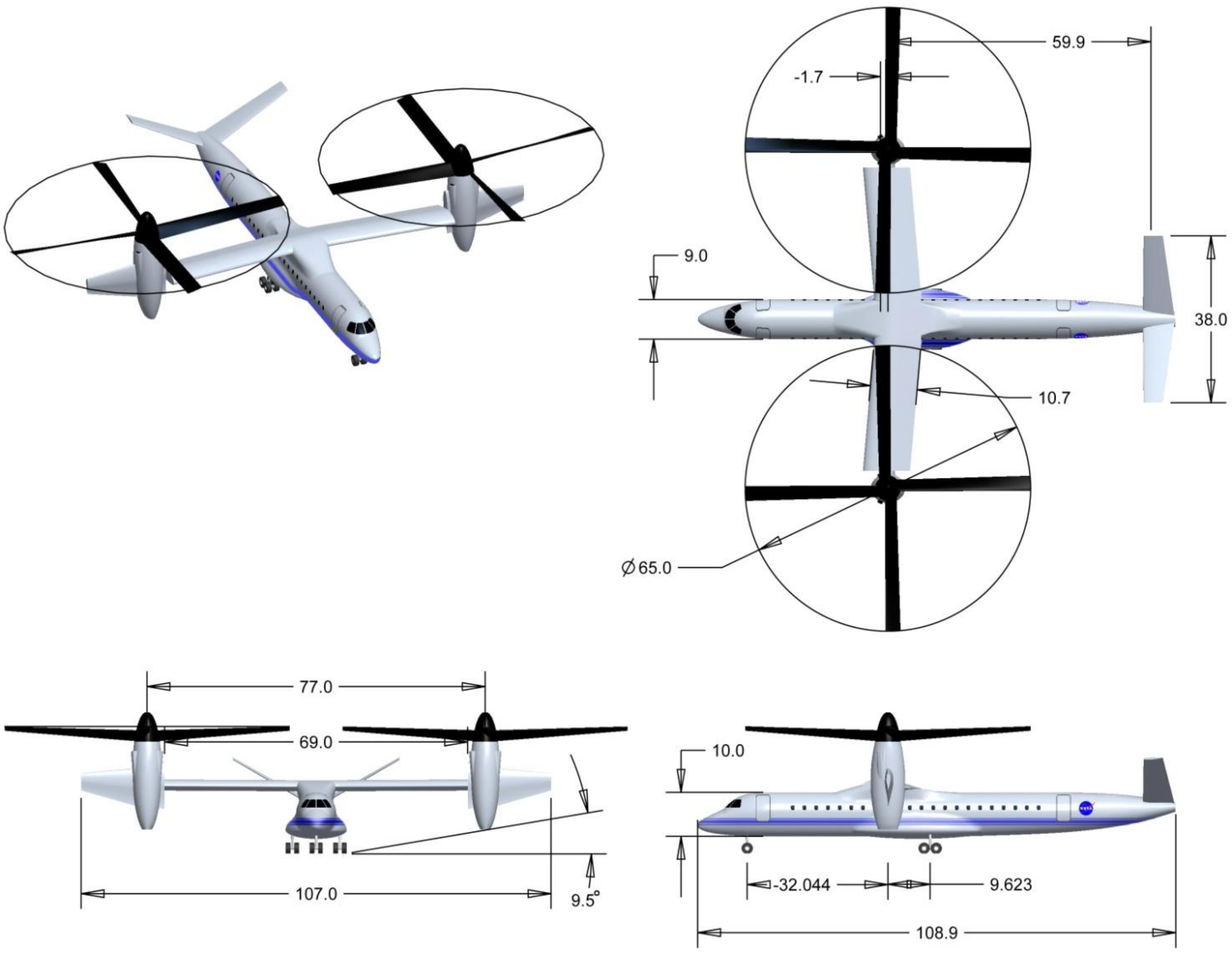

Fig. 1. The NASA Large Civil Tiltrotor, LCTR2 baseline version (dimensions in feet).

Common to all of these previous studies is the assumed gearbox weight penalty (10% increase for multi-speed versus fixed-ratio gearbox). Gearbox weight tends to be over twice the total engine weight. Work is progressing to reduce gearbox weight and the weight penalty for multi-speed capability; however those study options were not included in this effort. The LCTR2 is more sensitive to a given percentage weight increase in the gearbox than in the engine, hence a heavier but more efficient engine can more easily earn its way on to the design than can a multi-speed gearbox.

To try and answer questions raised by these previous analyses, NASA has continued VSPT research that has resulted in a potential VSPT design philosophy and initial performance estimates. VSPT work and efficiency potential are strongly functions of work factor (specific enthalpy extraction per stage divided by turbine tip speed squared) and variation in the flow incidence angle on the blade row. With the addition of weight and possibly some complexity, impressive improvements in power turbine power and fuel efficiency at reduced turbine rpm can be achieved. The theory and analyses supporting the VSPT performance levels used in this study are discussed more extensively in Ref. 6 and will be summarized in the Performance Models section.

Therefore, six engine / gearbox combinations were chosen for comparison, while maintaining a fixed mission profile. The six combinations deemed most likely to be used for LCTR2 include ACE using a multi-speed (shifting) gearbox and five variable-speed power turbine (VSPT) engine concepts. To avoid a double weight penalty, the engines using VSPT technology include only fixed-ratio gearboxes. The VSPT concepts include a minimum weight, two-stage, fixed-geometry VSPT and a matrix of either three or four turbine stages, and fixed or variable guide vanes. Performance and weight has been estimated for all engines concepts; details concerning engine performance and modeling will be covered in a subsequent section.

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. 7-9) 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 (reduced range of power turbine rpm variation while maintaining engine operability, power and fuel efficiency) using a fixed-ratio gearbox. These effects are all captured by NDARC, using rotor and engine performance models that incorporate the results of CAMRAD II and NPSS analyses.

Rotor efficiency was determined by Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics (CAMRAD II, Refs. 10 and 11). Engine performance and weight, with and without VSPT technology, was estimated with the Numerical Propulsion System Simulation (NPSS, Ref. 12) and Weight Analysis of Turbine Engines (WATE, Ref. 13). 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.

Rotor performance is influenced by wing/rotor interaction, and wing efficiency is strongly affected by the rotor wake (Refs. 2 and 14; see also Ref. 15). 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 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. For the different power turbine combinations (standard or VSPT), different power turbine component performance tables (tables of mass flow, work and efficiency characteristics vs. rpm) corresponding to that particular power turbine configuration were used. WATE uses engine state points over the expected operating profile from NPSS, along with geometry and technology factors, to generate engine weights. These performance and weight analyses were converted to equivalent, algebraic engine models for NDARC.

Aircraft and Mission

Table 1 and Fig. 2 summarize the LCTR2 mission requirements. For the present study, only one change was made since Ref. 2, in the way the mission requirements were interpreted and modeled in NDARC: the climb to cruise altitude is modeled as two equal-height segments for better trim convergence during sizing. (The OEI variations studied in Ref. 4 were not considered here, because they did not materially affect the tradeoff between propulsion concepts.)

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

Table 2 lists key constraints and assumptions imposed during the design. The three “minimum performance” constraints are the most important for sizing: minimum cruise speed of 300 knots at altitude, OEI hover at 5000-ft ISA +20° C altitude at design gross weight, and maximum gross weight takeoff at sea level standard conditions. In practice, an engine failure over the runway or landing pad would result in an immediate vertical landing and a failure while flying on the wing would be treated like any fixed-wing airliner. The critical OEI condition is then at low speed departing the landing site, but not yet converted to airplane mode. Under such conditions, the rotor inflow from even a low forward speed would reduce rotor power required below that for hover. Calculation of the exact worst-case condition would require much more extensive analyses of aeromechanics and handling qualities than are warranted here. For the present study, a 10% power reduction was assumed for OEI hover, implemented as a 10% increase in power available as a practical approximation. Nominal OEI contingency power is assumed to be 4/3 maximum continuous power, so the rotors are trimmed to 4/3×MCP×110% at the design OEI condition (from Ref. 2).

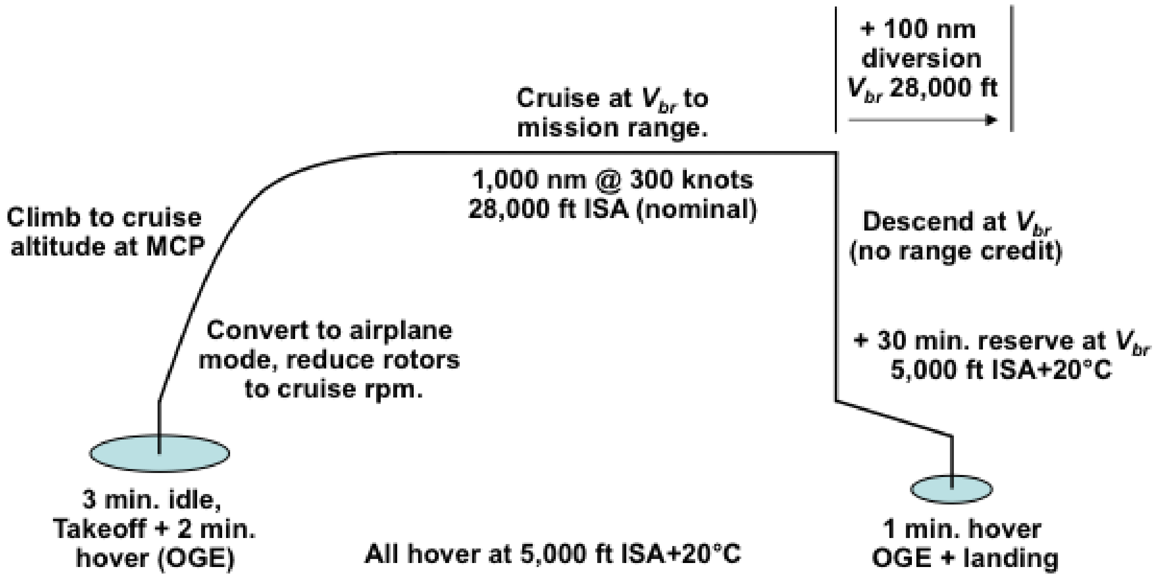

Fig. 2. LCTR2 nominal mission profile.

Table 2. LCTR2-03 design constraints for sizing.

Minimum Performance	
Max. takeoff weight at sea level standard, 100% MRP	
[a]OEI at 5k ISA+20°C, CRPx110%	
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
[b]Hover blade loading C_W/σ	0.151
[c]Cruise SFC, lb/hr/hp	0.3255
[d]Tip speed, hover, ft/sec	650

[a] Approximate OEI trimmed power not at MCP hover

[b] Set by maneuver requirement

[c] Advanced Conventional Engine specification

[d] Set by assumed future noise requirements

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. 16, which used CAMRAD II to derive the blade loading limit. The disk loading and wing loading were optimized in Ref. 17. 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 (Ref. 1).

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. 18). 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 at the nominal cruise speed and altitude (300 knots, 28,000 ft, ISA).

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.

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. 19. 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. 17, and incorporates further refinements to the mission model, as was first discussed in Ref. 4.

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 has not occurred. 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. 20 and 21. With some 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; empty weight includes fixed weights, notably avionics, and all subsystem weights, such as flight controls.

The first (2015) column in Table 3 represents the initial resizing with the optimized values of wing and disk loading from Ref. 17. The next, (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 rotor diameter limit and reduces gross weight by approximately 11.5%. All results in Table 3 and following include minor revisions and updates included in NDARC Release 1.5.

Performance Models

The rotor performance is summarized by Fig. 3 for the 28,000-ft cruise altitude. CAMRAD II was used to predict rotor performance in hover and cruise for each 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, span efficiency factor e (in the model used here, e does not include wing profile drag, which is accounted for separately). 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.

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

Engine: OEI Requirement:	2015 Hover	ACE Hover
Gross weight, lb	100,616	90,066
Empty weight, lb	65,660	59,378
Rotor weight, lb (both rotors)	8,146	7,067
Wing weight, lb (zero fuel)	8,776	8,103
Engines and drive train, lb	14,433	12,273
[a]Fuselage empty weight, lb	12,593	11,585
Mission fuel, lb	13,695	9,434
Engine power, (# engines x MRP HP)	4×6,406	4×5,624
[b]Rotor solidity (σ)	0.115	0.115
Rotor radius, ft	33.8	32.0
[c]Hover C_T/σ	0.162	0.159
Cruise C_T/σ	0.0676	0.0621
[d]Wing area, ft^2	958	858
Drag D/q, ft^2	34.4	31.9

[a] includes landing gear

[b] thrust weighted

[c] start of mission

[d] includes extensions

Figure 3 displays the rotor performance model in terms of cruise propulsive efficiency (η_p) and figure of merit (FM). These are actually the final values from NDARC; the values from the six, scaled concepts collapsed into a single curve for each parameter. LCTR2's cruise-optimized rotor has 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 4 displays the wing performance model as span efficiency factor e. At lower values of V_{tip}, e can be greater than one because of beneficial wing/rotor interference (Ref. 14). As traditionally calculated, e can also be greater than one because the rotor wake slightly increases local dynamic pressure above the free-stream value.

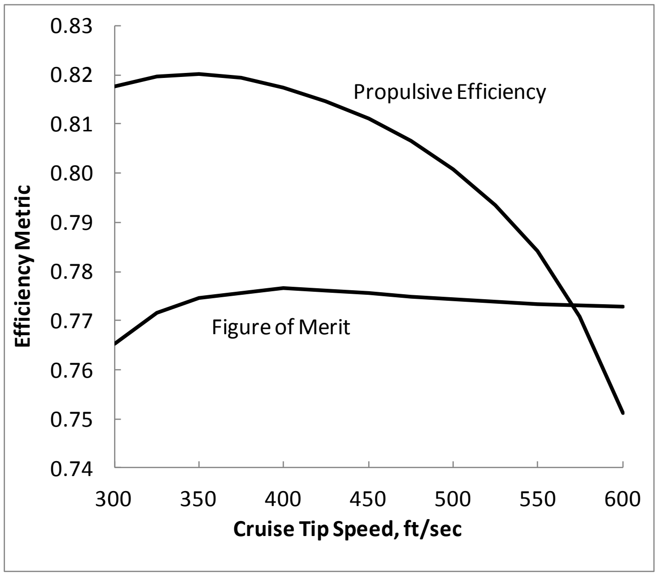

Fig. 3 Rotor performance versus rotor cruise tip speed; η_p is at 28,000 ft, 300 knots and includes wing/rotor interference; FM is at 5,000 ft ISA + 20°C.

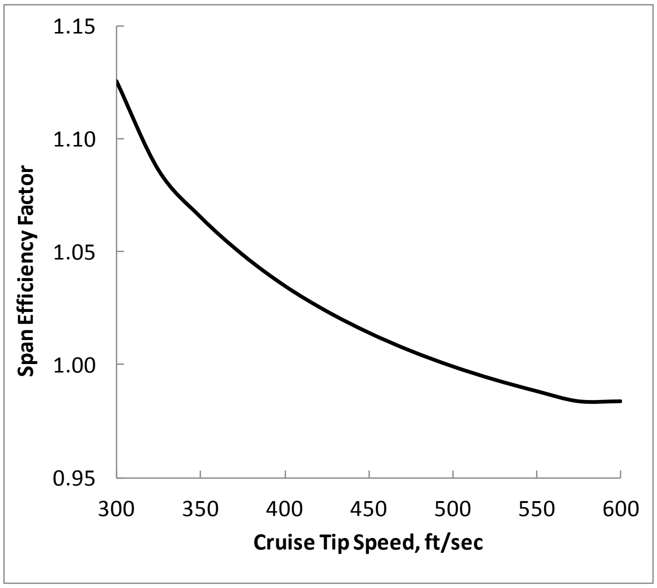

Fig. 4. Wing performance versus rotor cruise tip speed, calculated at 28,000 ft, 300 knots with full wing/rotor interference.

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. References 20 and 21 have detailed discussions of LCTR2 gas turbine cycle development and design details. The NPSS engine model assumed an overall pressure ratio of 40 and a maximum combustor exit temperature of 3000°F (at maximum rated power, MRP, SLS, ISA). Engine airflow is 29 lb/sec to develop a nominal 7,500 shaft HP (MRP, at SLS, ISA). NDARC resizes the engine to match the actual power required. The ACE engine has a two-stage power turbine, and the VSPT technology engine typically adds either one or two additional stages to the power turbine to achieve a wider operating speed range with acceptable efficiency. VSPT modeling and performance are discussed next.

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, but result in larger efficiency penalties for off-design operation. VSPT design enables efficient operation over a larger range of turbomachinery speeds. To minimize the efficiency penalty for such operation, the VSPT design process changes the blade airfoil shape and reduces turbine work factor (specific enthalpy extraction per stage divided by turbine tip speed squared) to be more tolerant of non-ideal flow incidence angles. VSPT designs are effectively trading peak efficiency for the ability to maintain efficiency and operability over a greater rpm range. Adding an additional stage (or stages) can be used to increase VSPT maximum efficiency and rpm range.

The amount of turbine blade airfoil shape change and number of additional turbine stages for an actual design is an iterative process, based on understanding all mission requirements. Since the LCTR2 is a cruise-dominated mission, and the desired rotor tip-speed reduction is already known, a faster and simpler method was used to make preliminary estimates for VSPT performance, based on work in Ref. 6. To maintain reasonable levels of turbine work factor, the power turbine should go from two stages for the conventional power turbine (ACE) to three or four stages for VSPT. Assuming the number of VSPT turbine stages, approximate cruise power requirements and cruise (minimum) rpm sets the maximum turbine work factor and VSPT cruise efficiency. Preliminary estimates for a two-stage FG-VSPT were included in the study. Stage loading would be very high for such a design, as well as efficiency losses at reduced rpm, which was expected to result in a non-competitive concept. Its size and weight were assumed to be the same as the ACE's two-stage power turbine.

The VSPT rpm is higher at hover, resulting in lower work factors than at cruise. These potentially significantly lower work factors reduce the VSPT sensitivity and efficiency losses from non-ideal incidence. The FG-VSPT designs have non-ideal flow incidence losses at hover, but because of the reduced work factors, these losses can be very small and as suggested in Ref. 6, actually result in slightly better VSPT efficiency at hover than at cruise. The VG-VSPT would use variable guide vanes to reduce this incidence loss at hover conditions, but preliminary estimates suggest only a further potential gain of 0.5% in VSPT efficiency at that particular operational point. Therefore, the cruise SFC of the VSPT is only a function of the number of stages, not whether it is fixed or variable geometry. The 0.5% increase in VG-VSPT hover efficiency increased hover MRP and was included in the engine power-to-weight ratio used in sizing.

For the ACE two-stage, standard power turbine, its low tolerance to non-ideal incidence would limit operation from 80 to 100% of design rpm (about 520 to 650 ft/sec rotor tip speed for a fixed-ratio gearbox); therefore the fixed-ratio option with ACE was not pursued. 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. 5). As modeled, FG and VG-VSPT concepts have similar characteristics. Engine shaft speed is here converted to equivalent rotor tip speed for ease of comparison with the rotor and wing performance plots (Figs. 3-4). The conventional engine (ACE) loses some efficiency over its limited operating range and was modeled only with a two-speed gearbox to keep the engine shaft speed near peak efficiency. The two-stage VSPT suffers significant efficiency losses at reduced tip speeds and was expected to result in a non-competitive design. The three and four-stage VSPT engines have negligible loss down to about 70% hover V_{tip}, and still maintain fairly high efficiencies at V_{tip} = 300 ft/sec. 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.

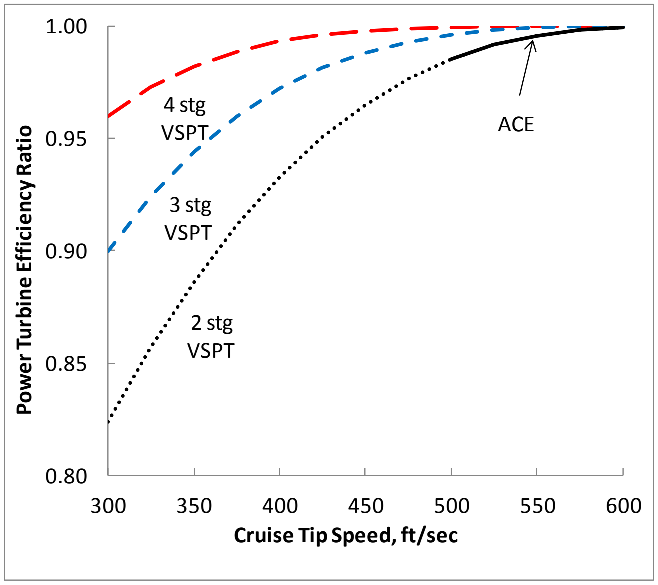

Fig. 5. Power turbine efficiency ratio, normalized to 100% rpm (MCP at 28,000 ft, 300 knots) versus rotor cruise tip speed.

For the reader more familiar with overall engine parameters, the effect of these turbine efficiency assumptions on engine cruise maximum continuous power (MCP) availability and SFC as determined by NPSS are shown in Figures 6 and 7. The three and four-stage VSPT designs use maps generated for a four-stage VSPT design; for the three stage design, only efficiency was adjusted based on the increased work factor from one less stage. Preliminary estimates for the two-stage VSPT used a different power turbine performance map that exhibited the expected, two-stage VSPT efficiency characteristics, noting some difference in mass flow characteristics vs. the other VSPT maps below 400 ft/sec. This effect was considered erroneous and not put into the NDARC model for that engine. These figures show that VSPT designs maintain engine operability over the desired rpm range, although there is some loss in power and fuel efficiency (higher SFC) as rpm is reduced. These losses increased at higher turbine loading levels (designs with fewer turbine stages).

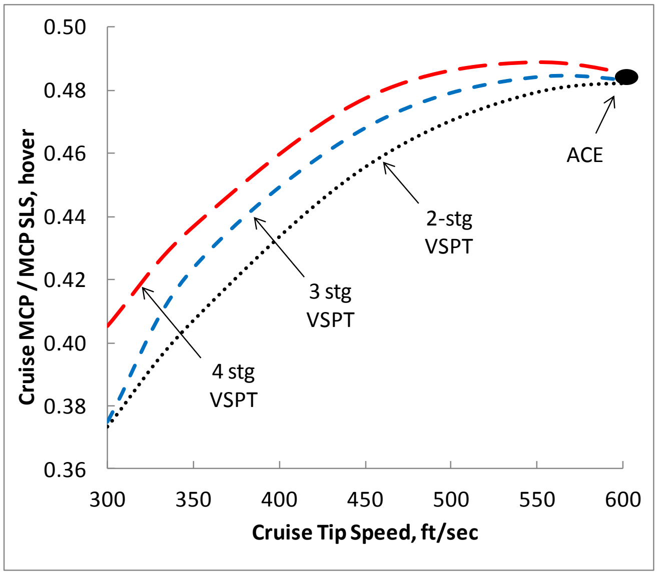

Fig. 6. Ratio of Cruise to Hover MCP (cruise at 28,000 ft, 300 knots) versus rotor cruise tip speed.

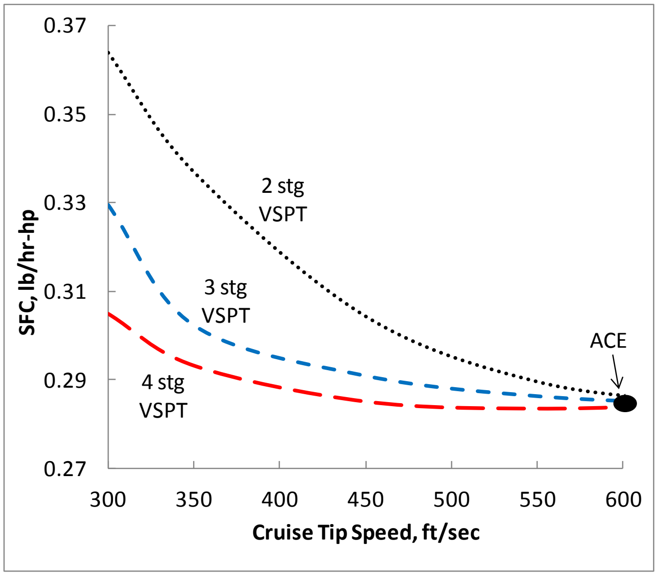

Fig. 7. Cruise SFC (cruise at 28,000 ft, 300 knots) versus rotor cruise tip speed.

Improved power capability and fuel efficiency are truly beneficial qualities, but adding turbine stages and complexity will also add to engine weight. Adding variable geometry to the VSPT is expected to increase the VG-VSPT component weight by approximately 20% over the FG-VSPT (maintaining the same number of turbine stages). Since the power turbine is about 16% of the total engine weight, adding stages and variable geometry has a significant effect on weight. Engine weight estimates using WATE are shown in Table 4. The two-stage FG-VSPT was assumed to be similar to the ACE baseline, while the three-stage VSPT engine is 8 or 13% heavier for FG and VG respectively, and the four-stage VSPT is 19% or 25.5% heavier. The VG-VSPT engines are about 5% heavier than their FG-VSPT versions. However, the increase in engine weight is mitigated by eliminating the two-speed gearbox, resulting in a lighter drive train.

Table 4. Total Engine Weight, lb (7,500 HP, SLS MRP)

	Fixed Geometry	Variable Geometry
2 stage	785	N.A.
3 stage	849	887
4 stage	932	985

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) and adds 10% to drive system weight (versus the fixed-ratio design). See Ref. 5 for details, including the discussion of a possible shift strategy. Reference 19 provides further information about the propulsion system studies upon which this paper relies.

Aircraft Sizing Comparisons

Figures 8-11 summarize the sizing results based on the component performance models described above. Design gross and empty weight, propulsion weight (sum of engine and drive system weights) and mission fuel burn are plotted against rotor cruise tip speed for the cruise condition of 28,000-ft altitude, 300 knots for the ACE and VSPT propulsion systems. Takeoff power and rotor radius closely track design gross weight and are accordingly not shown.

Most trends shown in Figures 8-11 are nearly flat around their optimum designs. Among the six propulsion concepts, optimum design gross weights varied 1% or less, and generally less than 2% in empty weight. The advanced engine and VSPT technology concepts have high power to weight and fuel efficiency; engine weights are less than 4% and mission fuel less than 9% of design gross weights for the optimum designs. This effectively minimizes the differences among the concepts. 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 some cases is slightly different from than that found in Refs. 2 and 4. The LCTR2 rotor design has scope for further refinement of twist in favor of hover, which could also affect the optimum cruise tip speed. 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.

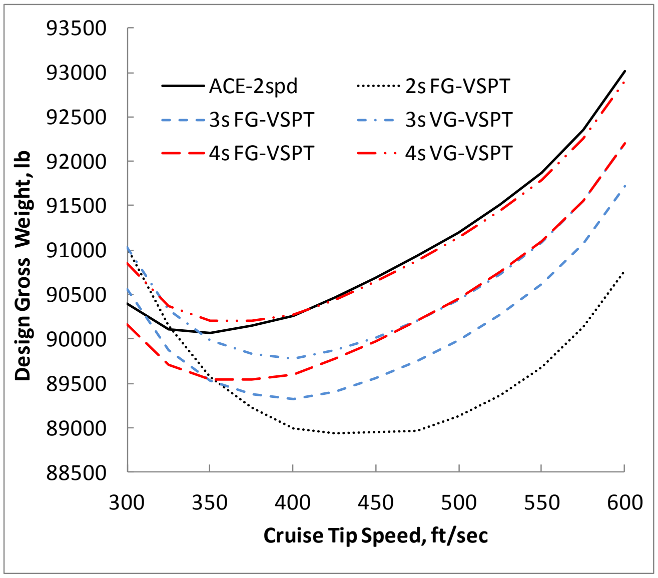

Fig. 8. Design Gross Weight versus rotor cruise tip speed.

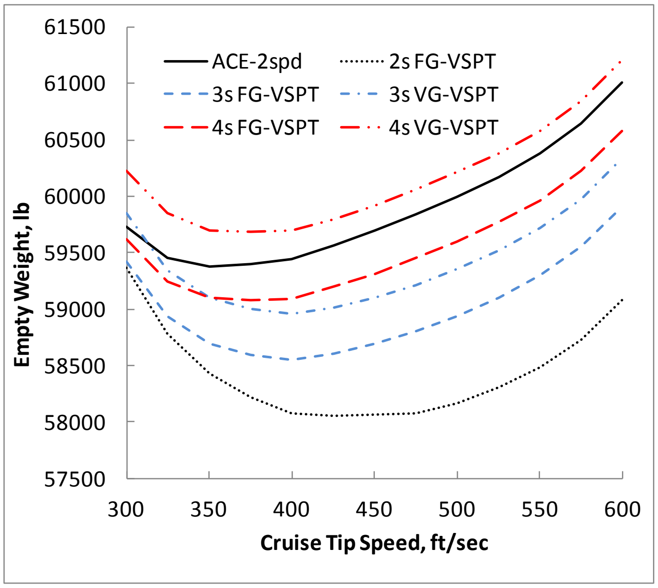

Fig. 9. Empty Weight versus rotor cruise tip speed.

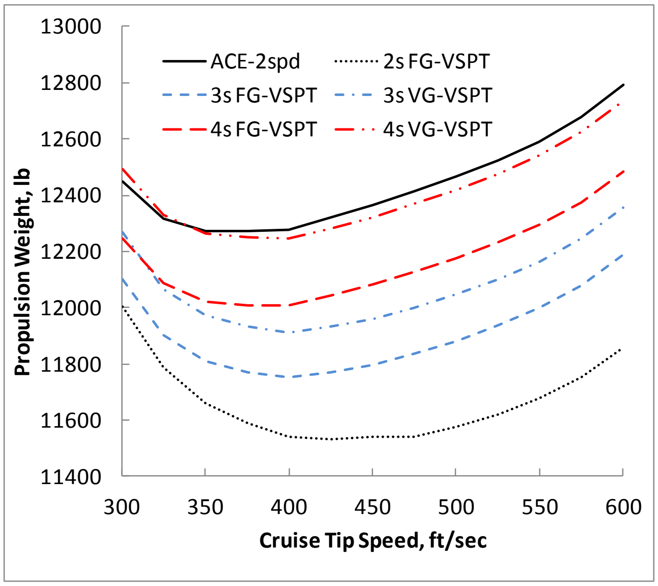

Fig. 10. Propulsion (engine and drive system) weight versus rotor cruise tip speed.

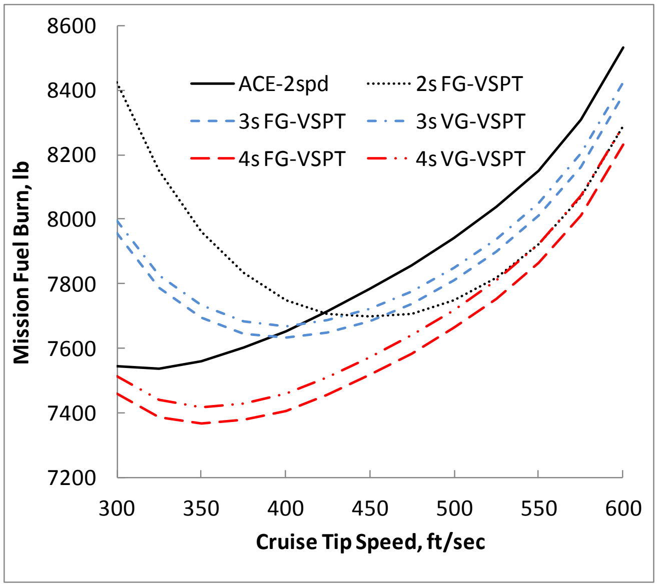

Fig. 11. Mission fuel burn versus rotor cruise tip speed.

Surprisingly, the minimum design gross and empty weight designs both occurred for the two-stage FG-VSPT with a fixed-ratio gearbox, thus highlighting the importance of minimum weight designs for vertical lift vehicles and missions. However, this concept also resulted in the highest optimum mission fuel burn and the optimum design around the high cruise tip speed of 450 ft/sec. Further review of the two-stage FG-VSPT power turbine weight and performance for these optimum solutions is warranted to verify model results. Preliminary performance assumptions for the two-stage FG-VSPT are the “best case” for this concept as it was expected that the large efficiency and power lapse at significantly reduced rpm would not result in a viable concept.

Additional potential power and fuel efficiency capabilities for the VG-VSPT concepts are not fully exploited by the LCTR2 mission requirements and design constraints. Therefore, variable geometry for the VSPT concepts only increased weights and fuel usage, versus their fixed-geometry counterparts Since both FG- and VG-VSPT concepts are designed at cruise, their cruise SFC is only a function of number of stages, not whether FG or VG. The slight increase in hover power turbine efficiency for the VG-VSPT concepts (0.5% increase in efficiency and MRP – takeoff power) was overwhelmed by the 20% VSPT component weight increase for the VG-VSPT over the FG-VSPT.

For nearly all cases, the engine weight increase of VSPT was offset by the lower weight of a single-speed gearbox and improved fuel efficiency, especially at reduced engine rpm. This is most exemplified by the four-stage FG-VSPT, which has the minimum mission fuel burn, followed closely by its VG-VSPT variant. These concepts have the highest propulsion weight trends over much of design space, except for the ACE with the two-speed gearbox weight. Results for the three-stage VSPT concepts generally fell between the two-stage and four-stage VSPT results; which isn’t surprising, since the three-stage VSPT weight and fuel efficiency characteristics fell between those other concepts.

The optimum rotor cruise tip speed is dependent upon the engine/gearbox combination, and is a tradeoff between rotor, wing and engine efficiency trends (summarized in Figs. 3, 4, and 7). For minimum empty weight, most concepts resulted in shallow minimum empty weight “bucket” for a range of V_{tip} from 350 to 425 ft/sec (except the two-stage FG-VSPT, the range of V_{tip} was 400 to 475 ft/sec). For minimum mission fuel, there was more variation in V_{tip} among the concepts, showing the compromise between the loss of engine fuel efficiency at reduced V_{tip} versus increased rotor efficiency. The range for optimum V_{tip} was 350 to 375 ft/sec for the four-stage VSPT concepts, 375 to 425 for the three-stage, and 425 to 475 for the two-stage FG-VSPT. For the ACE with two-speed gearbox, V_{tip} ranged from 300 to 375 ft/sec, to maximize the benefit of reduced V_{tip} propulsive efficiency and vehicle aerodynamics. The two-speed gearbox effectively decouples engine fuel efficiency from rotor speed, although at a significant propulsion weight increase, resulting in an increase in mission fuel at the lowest V_{tip}.

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 empty weight generally occurs slightly above the cruise tip speed for peak η_p (Fig. 3), and generally close to the tip speed for peak FM (also Fig. 3), except for two-stage FG-VSPT. Since the LCTR2 is a cruise-dominated mission, Fig.

12 shows how the design optimizes for higher aerodynamic efficiency as cruise fuel efficiency falls at lower V_{tip}. The difference in L/D_e among the concepts becomes negligible as fuel efficiency differences vanish. Because the FG- and VG-VSPT concepts exhibited similar cruise fuel efficiency characteristics (for the same number of stages) the FG- and VG-VSPT curves fall upon each other.

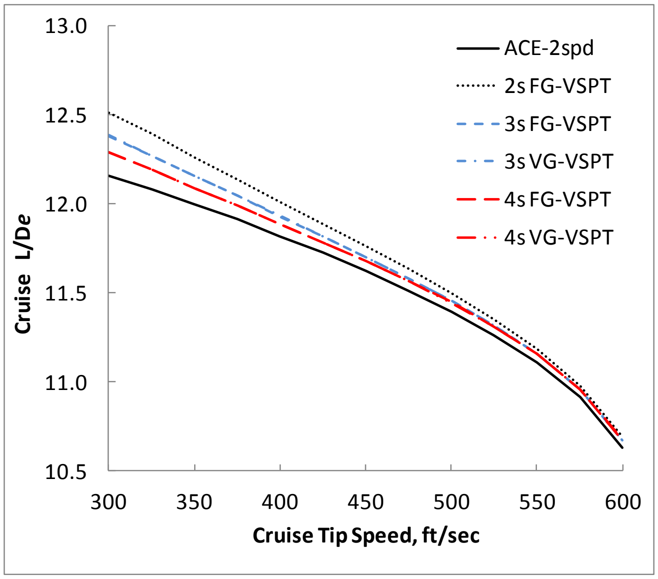

Fig. 12. Aircraft Cruise *L/D_e* versus rotor cruise tip speed.

Table 5 summarizes the differences between three propulsion system concepts for the LCTR2, here sized at the optimum cruise tip speed for each concept. The two-stage FG-VSPT was the best for most parameters, except fuel burn, although most differences among the three vehicles are small. Vehicle and component weights are less than 2% different, except for the propulsion system, where the four-stage, FG-VSPT engine weight is around 15% heavier than the other concepts. The difference in takeoff (MRP) power is less than 2%. For the two-stage power turbine concepts, the extra drive system weight for the two-speed gearbox increases its gross and empty weight over the fixed-ratio design, resulting in less than 2% fuel burn benefit. The four-stage, FG-VSPT is the most fuel efficient, consuming 3-5% less fuel, than the other concepts. This table reinforces the notion that a heavier but more efficient engine can more easily earn its way on to the design than can a multi-speed gearbox. All designs have effectively the same hover and service 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. The designs are also very close in maximum speed, the ACE with two-speed gearbox was slightly slower, but all concepts have significant speed margin above the LCTR2 300 knot cruise.

Consider the information in Table 5 from a development and operational costs standpoint. The former can be inferred from complexity of propulsion system choice, and empty, engine and drive train weights. The latter can be inferred from fuel burn for direct costs and engine and drive train weights for maintenance costs. An unexpected outcome results if the technology assumptions for gearbox weight and engine performance are not revised through further research or other potential technologies. The two-stage FG-VSPT is again the best design for most parameters, except fuel burn, where it is 3 to 5% higher. The economic tradeoffs are beyond the scope of this paper, but merit close study.

Table 5. Optimum LCTR2 design for three different propulsion concepts.

Propulsion Concept:	ACE 2-speed gearbox	2 stage FG-VSPT	4 stage FG-VSPT
OEI requirement	Hover	Hover	Hover
Gross weight, lb	90,066	88,946	89,541
Empty weight, lb	59,378	58,066	59,101
Rotor weight, lb (both rotors)	7,067	6,955	7,015
Wing weight, lb (zero fuel)	8,103	7,928	8,074
Engines, lb	3,047	3,006	3,472
Drive train, lb	7,901	7,201	7,254
[a]Fuselage empty weight, lb	11,585	11,477	11,534
Fuel burn, lb	7,561	7,697	7,365
Engine power (# engines x MRP HP)	4×5,624	4x5,547	4x5,592
[b]Rotor solidity	0.115	0.115	0.115
Rotor radius, ft	32.0	31.8	31.9
[c]Hover C_T/σ	0.159	0.159	0.159
Cruise C_T/σ	0.0621	0.0377	0.0616
[d]Wing area, ft^2	858	847	853
Drag D/q, ft^2	31.9	31.3	31.4
Rotor cruise tip speed, ft/sec	350	450	350
[e]Max speed at 28K ft, knots	344	355	352
[e]Service ceiling, ft	38,683	39,341	40,059
[e]Hover ceiling (HOGE), ft	7,400	7,400	7,400

[a] includes landing gear

[b] thrust weighted

[c] start of mission

[d] includes extensions

[e] 100% MCP

Conclusions

The Large Civil Tiltrotor (LCTR2) was sized with six different propulsion system concepts: an advanced, single-speed engine with a conventional power turbine layout (Advanced Conventional Engine, or ACE) using a multi-speed (shifting) gearbox; and five variable-speed power turbine (VSPT) engine concepts, comprising a matrix of either three or four turbine stages, and fixed or variable guide vanes; plus a minimum weight, two-stage, fixed-geometry VSPT. Sizing was performed for rotor cruise tip speeds from 300 to 600 ft/sec at a constant cruise altitude of 28,000 ft and a nominal 1,000-nm mission range. The hover OEI requirement sets engine size and drive system rating, thus the LCTR2 is overpowered for climb and cruise, therefore the rotors and engines can easily manage a rapid climb to cruise altitude. The sizing analysis was therefore a tradeoff between engine fuel efficiency and weight, and gearbox weight, varying with cruise tip speed. However, questions raised concerning FG-VSPT performance during the climb segment lead to the recommendation for further analyses to validate the FG-VSPT capability to meet LCTR2 climb segment requirements.

The advanced engine and VSPT technology concepts have high power to weight and fuel efficiency; engine weights are less than 4% and mission fuel less than 9% of design gross weights for the optimum concepts, minimizing differences among the optimum designs. This and previous studies assumed a 10% weight penalty for multi-speed versus a fixed-ratio gearbox. Since gearbox weight tends to be over twice that of the engine portion of total propulsion weight, the LCTR2 is more sensitive to a given percentage weight increase in the gearbox than in the engine. Thus, a heavier but more efficient engine can more easily earn its way on to the design than can a multi-speed gearbox.

Most trends are nearly flat around the optimum tip speed. Differences were minimal (< 2%) among the concepts among their minimum design gross weight and empty weight solutions; while the difference in minimum mission fuel for each concept was less than 5%. The trends in engine power and rotor radius closely followed those for design gross weight. Based on the performance and weight estimates for the FG- and VG-VSPT concepts, adding variable geometry did not improve weights or cruise performance over the fixed-geometry VSPT concepts. Design methodology for the VSPT concepts estimates that variable geometry slightly improves (0.5%) engine performance only in hover, which has little impact on mission fuel burn, but increases engine weight around 5%.

Minimum weights and mission fuel burns occurred for cruise tip speeds ranging from 350 to 425 ft/sec for the VSPT engine concepts. For the ACE with a two-speed gearbox, the optimums generally occurred at cruise tip speed ranging from 300 to 375 ft/sec. ACE engine fuel efficiency is constant because of the multi-speed gearbox (and its significant propulsion weight increase), so the vehicle optimums are driven mostly by propulsive efficiency and aerodynamic characteristics. The two-stage FG-VSPT resulted in the minimum design gross and empty weight solutions, but highest optimum mission fuel burn. The minimums were realized at cruise tip speeds from 425 to 475 ft/sec, which minimized engine efficiency losses at reduced rpm. As the superior performance of this concept was unexpected and its performance was not as rigorously estimated because it was considered non-viable, further effort is warranted to verify the two-stage FG-VSPT operability, performance and weight assumptions at such reduced rpms.

Reviewing optimum LCTR2 designs for three propulsion concepts: ACE with two-speed (shifting) gearbox and, two-stage FG-VSPT and four-stage VSPT with fixed-ratio gearbox, resulted in similar capabilities and similarity for many weight and performance parameters. However, the unexpected outcome was that the two-stage FG-VSPT with a fixed-ratio gearbox was the best among these propulsion concepts for most parameters, except for its 3 to 5% higher fuel burn. This warrants a deeper look at the underlying technology assumptions that led to this result.

Additional requirements were discovered during this preliminary assessment that could change technology and performance assumptions and study conclusions. Further effort is recommended to address questions and uncertainty in assumptions and subsequent results raised by this preliminary assessment. Another question still remaining is whether any reasonable improvement in the weight and performance of the LCTR2 with a two-speed gearbox with maintenance costs and operational constraints of in-flight shifting versus the increased cost and potentially increased maintenance of a four-stage VSPT compare to the increased fuel burn, but reduced weight and cost for the two-stage VSPT with fixed-ratio gearbox. Again, the economic tradeoffs are beyond the scope of this paper, but merit close study.

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