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Study and Sub-System Optimization of Propulsion and Drive Systems for the Large Civil TiltRotor (LCTR2) Rotorcraft

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ABSTRACT

In a series of study tasks conducted as a part of NASA's Fundamental Aeronautics Program, Rotary Wing Project, Boeing and Rolls-Royce explored propulsion, drive, and rotor system options for the NASA Large Civil Tilt Rotor (LCTR2) concept vehicle. The original objective of this study was to identify engine and drive system configurations to reduce rotor tip speed during cruise conditions and quantify the associated benefits. Previous NASA studies concluded that reducing rotor speed (from 650 fps hover tip speed) during cruise would reduce vehicle gross weight and fuel burn. Initially, rotor cruise speed ratios of 54% of the hover tip speed were of most interest during operation at cruise air speed of 310 ktas. Interim results were previously reported[1] for cruise tip speed ratios of 100%, 77%, and 54% of the hover tip speed using engine and/or gearbox features to achieve the reduction. Technology levels from commercial off-the-shelf (COTS), through entry-in-service (EIS) dates of 2025 and 2035 were considered to assess the benefits of advanced technology on vehicle gross weight and fuel burn. This technical paper presents the final study results in terms of vehicle sizing and fuel burn as well as Operational and Support (O&S) costs. New vehicle sizing at rotor tip speed reduced to 65% of hover is presented for engine performance with an EIS 2035 fixed geometry variable speed power turbine. LCTR2 is also evaluated for missions range cases of 400, 600, 800, 1000, and 1200 nautical miles and cruise air speeds of 310, 350 and 375 ktas.

INTRODUCTION

To explore the benefits and possibilities of tiltrotors for commercial operations, NASA contracted Boeing to evaluate propulsion system concepts for the NASA Large Civil Tilt Rotor (LCTR2) concept vehicle shown in Figure 1. Vehicle characteristics include a takeoff gross weight (GW) weight of 107,700 lb, with 65 foot diameter rotors near the wing tips. The payload for NASA's LCTR2 is 19,800 lb, which includes 90 passengers and baggage. The propulsion system is primarily contained in the two nacelles with two engines per nacelle. The nacelles tilt forward to cruise after a vertical take-off or hover. The LCTR2 design rotor tip speed (Vtip) is 650 fps during takeoff / hover to maintain high rotor efficiency and to manage noise levels. The vehicle rotor speed then decreases to a 350 fps rotor tip speed for cruise, or 54% of the hover RPM.

Figure 1: Conceptual view of LCTR2

Previous summaries of study methods and results were presented at AHS conferences (references 1 & 2). The summaries included an evaluation of LCTR2 vehicle sizing and performance characteristics over a range of propulsion system variations. Three engine and drive system technology levels were studied in this effort: commercial off the shelf (2015 / COTS), and technology levels expected for 2025 entry into service (EIS), and 2035 EIS. A primary goal of this study was to identify favorable engine and drive system concepts to achieve a 54% rotor cruise tip speed variation. The summary also reported on the development of sizing methodology, generation of engine data for COTS and advanced technology engines (EIS 2025 and 2035), development of the drive system concept architecture and characteristics, analysis of prop-rotor performance, assessment of advanced technologies, as well as identification of technology challenges and needs for the overall system.

Rotor speed variability of 100%, 77% and 54% was achieved with two methods: changing gear ratios in the output/transmission drive train and/or using highly variable output speed gas turbine engines. Table 1 contains the combinations of engine and drivetrain options that were previously reported.

TABLE 1: ROTOR CRUISE TIP SPEED

Engine Technology (for all combinations)	Rotor Cruise Tip Speed, (%)	Engine Cruise RPM (%)	Drive System Cruise RPM, %
COTS 2015 Engine	650 fps, (100%)	100%	100%
EIS 2025 Engine 1*	500 fps, (77%)	100%	77% (2-speed)
		77%	100%
EIS 2035 Variable Geometry Engine 1* & EIS 2035 Fixed Geometry Engine 2*	350 fps, (54%)	100%	54% (2-speed)
		77%	70% (2-speed)
		54%	100%

1* refers to variable geometry 'Variable Speed' power turbine technology

2* refers to fixed geometry 'Variable Speed' power turbine technology.

The conclusions reached from the initial study, given the limitations of the methodology and the constraints of the configuration, were that the lightest vehicle weights were produced from advanced engines with rotors operating near 500 fps tip speed. The lightest GW design was 91,923 lb, for the 500 fps cruise tip speed with a single-speed transmission and 77% engine RPM with the 2035 fixed geometry (FG) variable-speed power turbine (VSPT). The second lightest GW design was slightly heavier at 91,989 lb. It also occurs at the 500 fps cruise tip speed, but with a 2-speed transmission and 100% engine RPM. Vehicle GW for the 2035 engine with variable geometry (VG) VSPT was 1540 lb heavier than the 2035 FG-VSPT engine at Vtip= 500 fps. The 350 fps rotor tip speed cases sized very close to each other, between 93,900 lb and 94,900 lb GW.

The most dramatic effects on vehicle sizing were obtained with advanced engine technology, which resulted in reduced fuel burn, and the most favorable operating condition was near 500 fps tip speed with cruise speed of 310 ktas. Generally, the study results were insensitive to the method of speed reduction, nearly the same sizing results were obtained whether the speed reduction was achieved with reduced engine speed or with two speed transmissions. To further understand the sensitivities to tip speed, engine and gearbox speed reduction method, and mission parameters, additional analysis was performed,

The current paper reports results from additional recent tasks accomplished by Boeing under contract to NASA. Using only the EIS 2035 fixed-geometry variable speed power turbine (FG-VSPT) as the baseline engine, tasks included the following:

- Vehicle sizing for a new 65% rotor cruise tip speed case.
- Vehicle sizing for missions range cases of 400, 600, 800, 1000, and 1200 nautical miles and cruise air speeds of 310, 350 and 375 ktas.
- Operating and Support (O&S) cost information for new sizing conditions

Additional details of the analysis methodology, notional propulsion, rotor and drive system configurations, and vehicle sizing data are reported as well.

BACKGROUND

Previous Results

Configurations and technology levels of Table 1 were evaluated to find the propulsion and drive system configuration that results in minimum vehicle weight and fuel burn for the three technology levels evaluated. Operational variables affecting that balance include engine speed reduction fraction, drive system speed reduction fraction, technology factors, efficiencies, and configuration variables (fuel quantity, vehicle size).

Mission characteristics of range, cruise speed, and altitude were constrained to the original NASA design. Climb and cruise segments drove the fuel consumption in this study, which had a major effect on rotorcraft sized for long-range such as the LCTR2. Results of the sizing studies, engine and drive system configuration data, and study methodologies were presented previously, and the sizing comparison for the FG-VSPT study at 310 ktas airspeed are shown in Figure 2 and Figure 3 in this report.

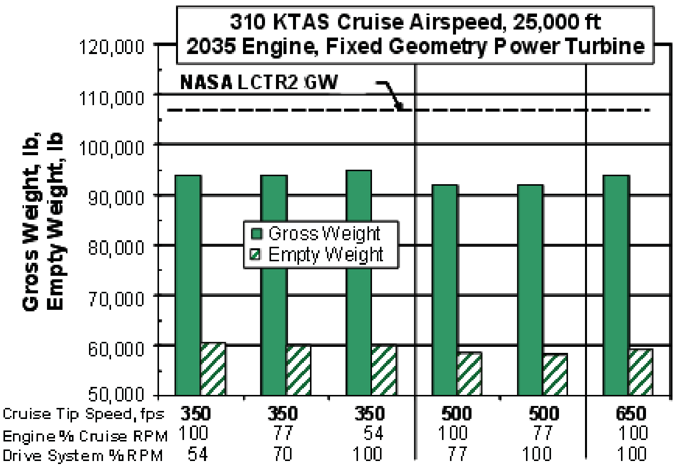

Figure 2: 2035 FG-VSPT Engine – Effect of Rotor Tip Speed and Engine/Drive System RPM on GW

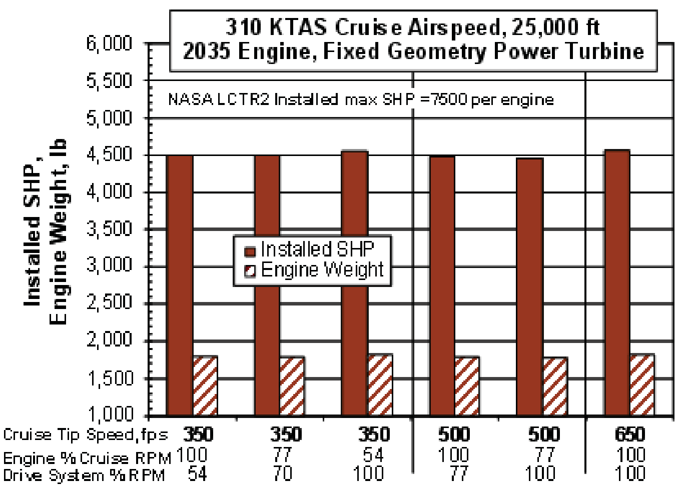

Figure 3: 2035 FG- VSPT Engine - Installed SHP and Weight

New Analysis

Table 2 presents the updated matrix of rotor cruise tip speeds, combinations of drive system and engine rpm, and technology levels used to evaluate the LCTR2 overall vehicle size, geometry, performance, installed engine HP, and rotor efficiency. This table lists all conditions that were studied with the most recent unreported parameters of interest highlighted. All new sizing cases are conducted at EIS 2035 technology level with the FG-VSPT engine.

Previous studies by NASA investigated rotor speed reduction to 54% (350fps). Boeing's initial study results found that 500 fps tip speed rotor speed provided a lighter weight air vehicle design for the constraints and conditions imposed. To further articulate this study, an intermediate rotor speed of 422 fps (65%) was analyzed in this new work and is presented in this paper. Aircraft sizing results for airspeeds of 350 ktas, and 375 ktas. are also included to understand sensitivities encountered with higher operating speeds. Projected (relative) O&S costs are also presented to provide understanding of the economic effects in this design exploration.

Table 2: Design Matrix of Engines, Technology and Cruise RPM Combinations

Technology →

		2015 EIS		2025 EIS		2035 EIS VGPT		2035 EIS FGPT	
Cruise Airspeed	V tip fps	Eng % RPM	Dr. Sys % RPM	Eng % RPM	Dr. Sys % RPM	Eng % RPM	Dr. Sys % RPM	Eng % RPM	Dr. Sys % RPM
375 kt	350							100	54
								77	70
								54	100
350 kt	350							100	54
								77	70
								54	100
310 kt	350	100	54	100	54	100	54	100	54
		77	70	77	70	77	70	77	70
		54	100	54	100	54	100	54	100
	422							100*	65
								65	100
	500	100	77	100	77	100	77	100	77
		77	100	77	100	77	100	77	100
	650	100	100	100	100	100	100	100	100

TECHNICAL APPROACH

Sizing Methodology

Engine models, rotor system performance models, and drive system weight and efficiency charts were used by the sizing model and are covered in previous technical papers and a project report. The sizing methodology used in the latter portion of the study remained the same. Boeing used customized spreadsheets to evaluate the aircraft size and performance. This sizing tool modeled most of the VASCOMP (reference 3) performance and sizing procedures in a format that allowed Boeing to perform "Concept Evaluation" analysis for the LCTR2 air vehicle. From this spreadsheet, aircraft weight, engine performances, rotor performances, mission performances, and overall vehicle sizing are extracted.

Engine Model

Engine models were provided by Rolls-Royce in spreadsheet format. Available shaft horsepower engine data was tabulated at Maximum Rated Power (MRP) Intermediate Rated Power (IRP), and Maximum Continuous Power (MCP) versus altitude and Mach number (all climb and cruise flight segments were at International Standard Atmosphere (ISA) conditions). This previously supplied engine data was extended to cover the 65% speed condition added to the study. The engine used in this study is a Rolls-Royce engine designated PD628. This engine has Advanced Versatile Affordable Advanced Turbine Engines (VAATE) advanced technology with high overall pressure ratio (>30) and two-spool core. The turbine was optimized for 90% speed operation with part speed performance down to the 54% RPM condition. It weighs 807 lb with a reference SHP of 8086 HP per engine. A graphical representation of that engine model at 65% operating speed is shown in Figure 4.

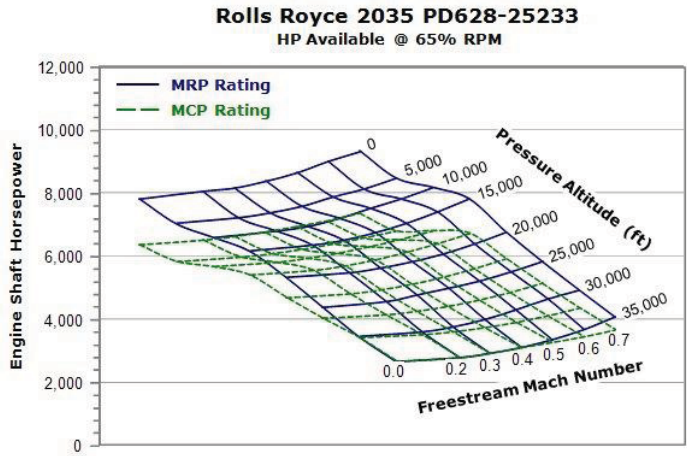

Figure 4: 2035 FG-VSPT Engine Power Available at 65% RPM

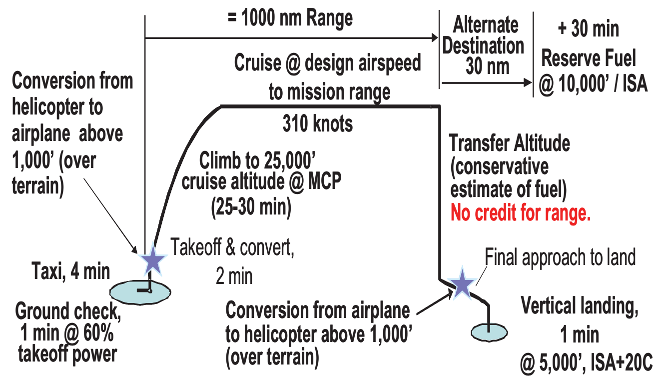

Figure 5: Mission Profile

Mission Fuel and Profile

The installed engine power required for each LCTR2 sizing case was scaled to the greater of hover takeoff power or cruise power. Engine scaling assumed specific fuel consumption (SFC) was preserved for the same relative power, altitude and Mach number. Power required for LCTR2 cruise performance accounted for the Rolls-Royce engines' residual jet thrust. Fuel flow was obtained from referred fuel flow versus referred power, against Mach number and altitude. Mission fuel was calculated for each LCTR2 mission segment and summed up to total fuel required. Fuel was calculated at seven (7) climb altitudes, sequentially evaluated at the corresponding GW during climb, and at four (4) cruise segments.

The NASA mission profile for the LCTR2 was used to size all cases. No attempt was made to find or use a more optimum altitude, cruise airspeed, or to evaluate other mission ranges. The LCTR2 sizing mission profile is described in Figure 5.

- 5 minute warm up at IRP power at 5,000'/ISA+20°C
- 2 minute hover takeoff at 5,000'/ISA+20°C
- Climb to 25,000' cruise altitude at MCP, ISA
- Cruise at 25,000'/ISA, 310 ktas to a range of 1000 nmi
- Vertical descent (no time, no fuel, no distance)
- 1 minute hover landing at 5,000'/ISA+20°C
- 30 nm cruise allowance for alternate destination, Vbr (airspeed (velocity) for best range) at 25,000'/ISA
- 30 minute reserve fuel at Vbr, 10,000'/ISA

Drive System

The LCTR2 drive system configuration remains the same as the previous work. It has 4 engines with 2 at each nacelle. It consists of 5 transmissions: a left hand (LH) and right hand (RH) proprotor gearbox, LH and RH Tilt Axis Gearbox, and a mid-wing gearbox. For portions of this study, it is assumed that the speed reduction is achieved using the drive system speed reducer. To accomplish this, a speed changing gearbox is placed at each engine input to the proprotor gearbox as shown in Figure 6. A similar baseline configuration without two speed capability is also used for the analysis cases where all speed reduction is accomplished by the engine.

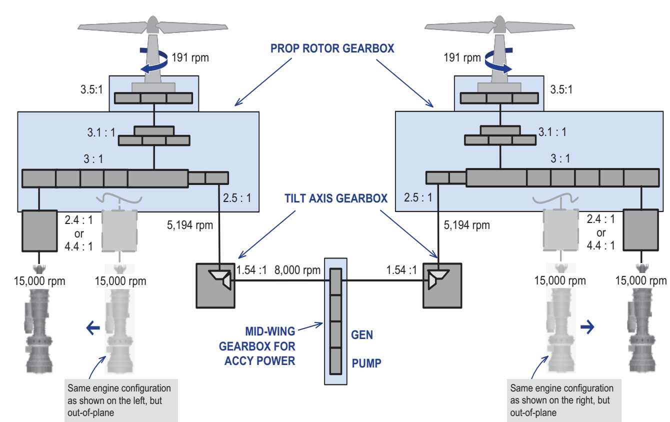

Figure 6: Drive System Schematic

Cruise Propulsive Efficiency

Boeing constructed models of three additional rotors for this study based on NASA LCTR2's rotor airfoils and blade platform. Twist distributions were modified for the 422 fps rotor speed case for airspeed of 310 ktas. Two rotor models were constructed to evaluate the impact of higher cruise airspeeds on the LCTR2 size, GW, and cost; one for 350 ktas cruise and the other for 375 ktas cruise. Both rotor designs applied the 350 fps rotor cruise tip speed, which corresponded to 54% RPM where existing engine data was available. The helical blade tip Mach number is 0.71 at 25,000 ft, 375 ktas cruise airspeed, so this design required thinner airfoils over the blade radius to avoid adverse drag divergence. See Figure 7 for an example of blade distribution at 310 ktas. Maps of rotor cruise efficiency are illustrated in Figure 8 through Figure 10.

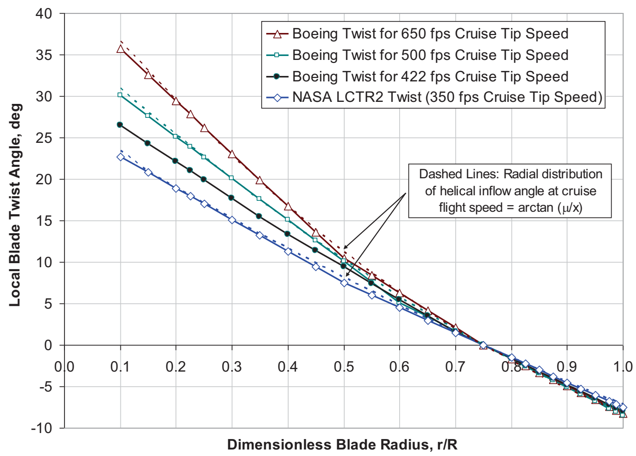

Figure 7: Comparison of Rotor Blade Twist Distribution

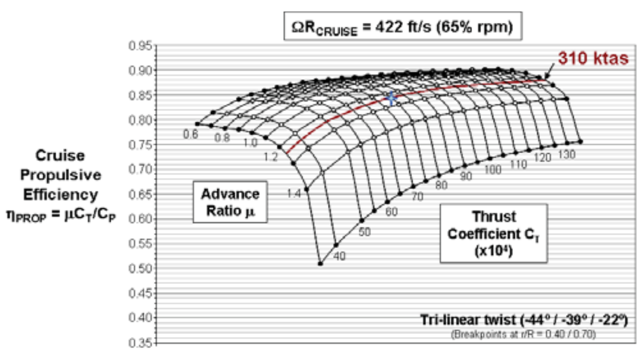

Figure 8: Rotor Cruise Propulsive Efficiency for 422 fps Cruise Tip Speed Design at 310 ktas Airspeed

For the two additional rotors operating at increased cruise airspeeds of 350 ktas and 375 ktas, Boeing retained the NASA parameters for cruise tip speed of 350 fps and its relative chord distribution. Blade geometric twist was modified to better align local airfoil sections with helical inflow angle at the two higher flight speeds. During this process, additional consideration was given to the attendant increase in local blade Mach number, especially over the inboard portion of the rotor blade. As flight speed is raised from 310 ktas to 350 ktas and beyond to 375 ktas, the local Mach number at the blade root station (r/R = 0.10) increases from 0.51 to 0.58 and 0.63, respectively.

Inspection of the properties provided by NASA for the LCTR2 28% thick blade root airfoil indicates that this airfoil cannot operate above Mach 0.60 at any angle-of-attack without incurring significant compressibility penalties. Comparison of this limit with the local Mach number conditions at the blade root suggests that at 350 ktas this airfoil will operate close to its drag divergence boundary, while at 375 ktas this airfoil will operate entirely beyond this limit and unduly penalize rotor performance at this operating condition. For the purpose of this study, the original NASA LCTR2 airfoil placement was retained for the 350 ktas rotor design, but was modified for the 375 ktas design by eliminating the 28% thick airfoil from the blade root and re-distributing the remaining airfoils along the inner portion of the span.

Upon re-twisting the blade to align the local airfoil sections with helical inflow angle, rotor cruise predictions were made with the Boeing B-08 rotor performance program at representative thrust conditions to identify the associated blade lift coefficient levels. From these calculations, a representative value of Cl = 0.30 was identified, and this value was used to determine the limiting outboard radial station at which the 18% thick LCTR2 airfoil could be tolerated without exceeding its performance limits. A limit of r/R = 0.50 was identified, and the blade thickness distribution of the 375 ktas rotor was tapered from 18% at r/R=0.225 to 12% at r/R=0.50.

The Boeing 350 ktas cruise airspeed rotor design had a tri-linear twist (-33.1°/-30.5 / -27°) to closely match the helical inflow distribution with a 350 fps tip speed. The LCTR2 solidity, reference blade planform and airfoil distribution were maintained. Breakpoints in the piecewise linear twist distribution were located at r/R = 0.45 and 0.70.

The Boeing rotor design for 375 ktas cruise airspeed had a tri-linear twist (-30.8°/ -29º /-25.8°) with the LCTR2 solidity and reference blade planform. Breakpoints in the piecewise linear twist distribution were located at r/R = 0.40 and 0.70.

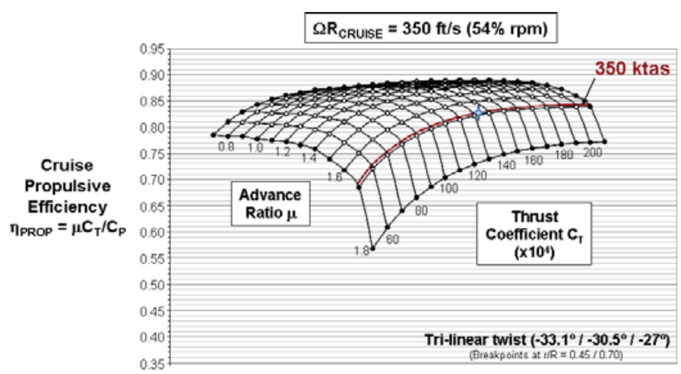

Figure 9: Rotor Cruise Propulsive Efficiency for 350 ktas Cruise Airspeed Design, 350 fps Vtip

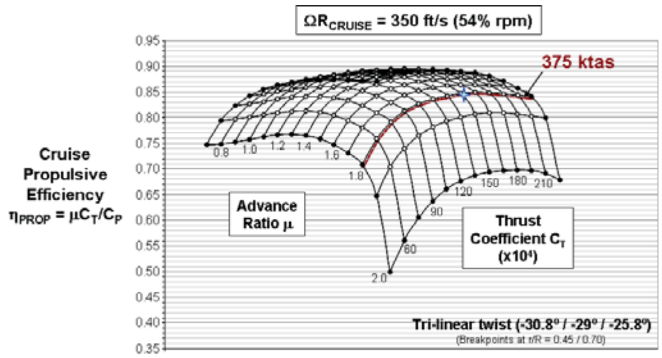

Figure 10: Rotor Cruise Propulsive Efficiency for 375 ktas Cruise Airspeed Design, 350 fps Vtip

O&S Cost

Cost was estimated with the PRICE Estimating Suite, the identical PRICE model that was applied in reference 4 for previous civil tiltrotor analysis. Relevant output from the Excel sizing analysis was linked to the PRICE Estimating Suite and run in Phoenix Integration's ModelCenter environment. The cost model assumed a fleet of 300 aircraft operating 2500 flight hours per year. Indirect operating costs were based on a service life of 20 years and a 7.5% interest rate, but this study focused on direct costs.

The metric of Direct Operating Cost (DOC) per Available Seat-NM (DOC/ASM) is used by commercial passenger airlines to track the financial health of daily operations. The revenue side of the balance sheet is revenue per available seat-nmi, which is essential to the airline's financial viability.

Cash Operating Cost comprises both direct and indirect operating cost. The term Cash DOC refers only to the direct operating cost components, including fuel, oil, maintenance, landing fees, crew expenses, supplies and catering, flight crew and cabin crew salaries, as shown in Table 3.

The ground rule utilization of 2500 flight hours per year actually required 2.5 flight crews and cabin crews per aircraft because air crews are limited to 1000 flight hours per year. Annual crew salaries came from Conklin & deDecker ("The Aircraft Cost Evaluator" http://www.conklindd.com). They were multiplied by 2.5 crew sets and then divided by 2500 FH/aircraft/year to express them as $/FH, per aircraft in the fleet.

Mission fuel requirements came from the Excel sizing analysis, depending on the rotorcraft GW, cruise altitude and airspeed, and, as shown in this study, are greatly affected by advanced engine technologies. The cost of fuel and oil, flight crew salaries, cabin crew salaries, landing fees, crew expenses, and supplies and catering were added to the PRICE output with a Post-Price module in ModelCenter to arrive at Cash DOC/ASM.

Table 3. Definition of Cash DOC

	OPERATING COSTS		
Cash DOC	Direct Operating Cost (DOC)		
		Fuel & Oil	
		Maintenance *(Price)*	
			Airframe, Labor & Parts
			Engine Restoration
			Dynamic Systems/Life Ltd
			Burden
		Landing Fees	
		Crew Expenses	
		Supplies-Catering	
	Indirect (Fixed) Operating Cost		
		Flight Crew	Salaries + benefits
		Cabin Crew	Salaries + benefits
		Hanger Costs	
		Hull Insurance	
		Depreciation	
		Financing	
		Training	
		Computer Mgt pgm	
		Refurbishment	

RESULTS

LCTR2 Sizing

The LCTR2 was resized with the 2035 FG-VSPT engine for all rotor cruise tip speeds previously evaluated and the additional rotor design with a 422 fps tip speed (65% of hover rpm) at the baseline airspeed of 310 ktas to better define the optimum rotor cruise tip speed. Results for vehicle GW are shown graphically in Figure 11 and results for engine power and weight are in Figure 12. Minor adjustments were made to some of the study parameters that resulted in a small effect on previously reported sizing results for tip speeds at 350, 500, and 650 fps.

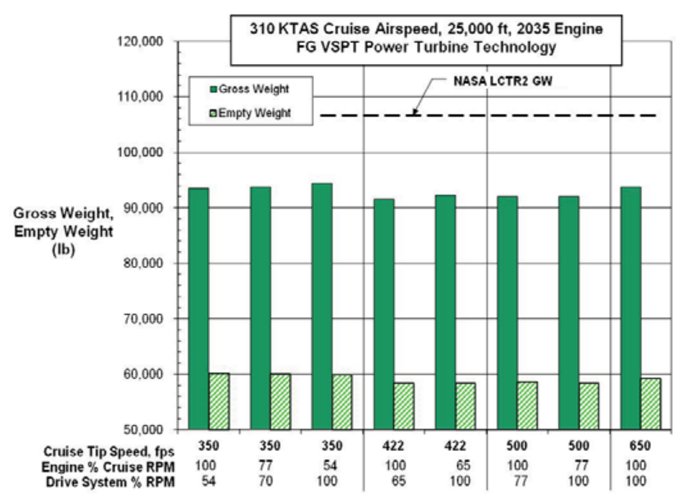

Figure 11: 2035 FG VSPT Engine: Rotor Tip Speed and Engine/Drive System RPM Effect on GW

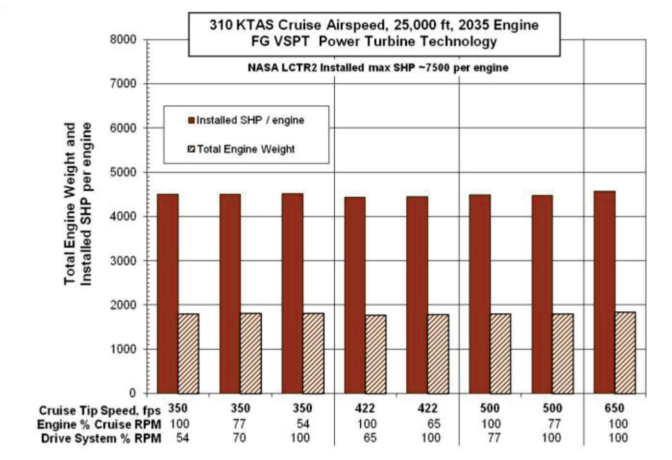

Figure 12: 2035 FG-VSPT Engine Installed SHP and Weight

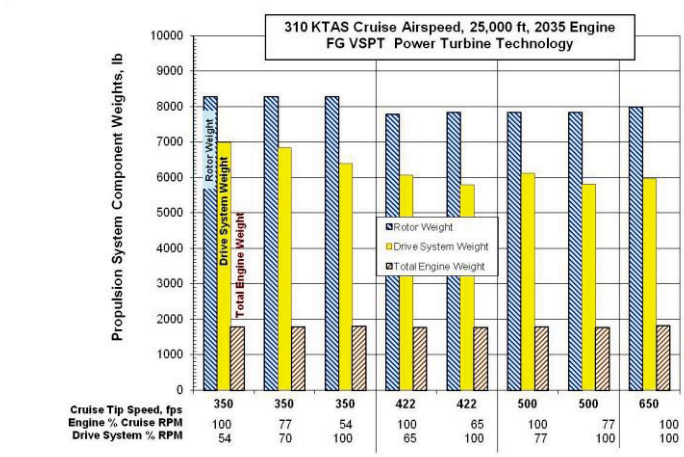

Figure 13: Propulsion System Component Weights for 2035 FG-VSPT Engine

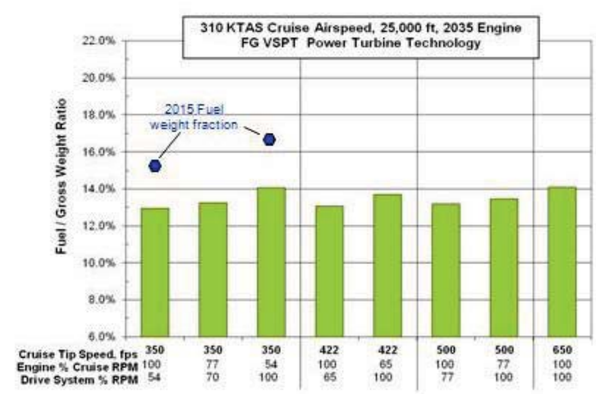

Figure 14: Mission Fuel Weight Fraction for 2035 FG-VSPT Engine

As anticipated, the new sizing case at 422 fps provided the lightest aircraft sizing point by a narrow margin. The 422 fps and 500 fps rotor tip speeds had a small spread of only 648 lb between them, rather clearly showing that the optimum rotor cruise tip speed is in this 422 fps to 500 fps range. In contrast to previous results in this study, the lowest weight option at the 422 fps tip speed is obtained with a 2 speed drive system used to obtain the 65% reduction, and engine operating at 100% speed.

Confirming previous analysis, the 2035 FG-VSPT engine resulted in an average 2400 lb lower GW than the 2035 (Variable geometry) VG-VSPT engine for all combinations of tip speed and engine-drive system RPM. The minimum GW drops down to 91,612 with the FG-VSPT and 422 fps tip speed.

The closest result for 350 fps was 1912 lb heavier than the minimum GW case just mentioned. There was a very small spread of rotor cruise propulsive efficiency from 350 fps, 422 fps, and 500 fps rotors, which is 0.841 to 0.848 at the 310 ktas design cruise airspeed. Cruise propulsive efficiency for the 650 fps case was notably lower, 0.76.

Figure 13 graphs the propulsion system component weights, i.e. rotor weight, drive system weight, and total engine weight. The combination of rotor and drive system weight clearly overshadows the engine weight. The 2035 drive system is estimated to weigh about 12.5% less than the 2015 drive system, for a given gear reduction and power rating. Sizing results showed the average 2015 drive system weight to be about 0.41 lb/rated HP, whereas the average 2035 drive system weighed 0.344 lb/rated HP, a significant weight reduction.

Figure 14 shows the variation of the fuel weight as a fraction of GW. The 2035 FG-VSPT engine is considerably lighter than either of the other engines, bringing the empty weight down, and it has lower fuel flow. These fuel weight fractions are much lower than the 2015 fuel weight fractions spotted on the graph.

Sensitivity to Increased Airspeed and Range

Tasks were completed to explore the sensitivity of LCTR2 to design cruise airspeed and mission range, in concert with estimated operational costs. Using the best engine match for LCTR2, the 2035 FG-VSPT engine, three design airspeeds are evaluated;

- 310 ktas with the 422 fps tip speed rotor designed for 310 ktas cruise airspeed.
- 350 ktas with the new 350 fps tip speed rotor designed for 350 ktas cruise airspeed.
- 375 ktas with the new 350 fps tip speed rotor designed for 375 ktas cruise airspeed.

Aircraft Weight Growth with Design Airspeed and Range

The LCTR2 was resized at each design airspeed for mission ranges of 400 nautical miles (nmi) up to 1200 nmi, including estimated operating costs. The carpet plot in Figure 15 quantifies the growth of vehicle GW for higher design cruise airspeeds (more required SHP) and for longer range (increased mission fuel). Both trends are as expected.

The growth of GW with design airspeed is dramatic. Considering the 1000 nmi mission range, GW grows from 91,600 lb at a 310 ktas design airspeed to 110,000 lb at a 350 ktas design airspeed, on up to over 125,000 lb at a 375 ktas design airspeed. This increase was driven by the added fuel requirement, and compounded by increased installed SHP to satisfy higher cruise airspeeds. Increasing mission range from 1000 nmi by 20% to 1200 nmi increased the takeoff GW by 5% to 7%.

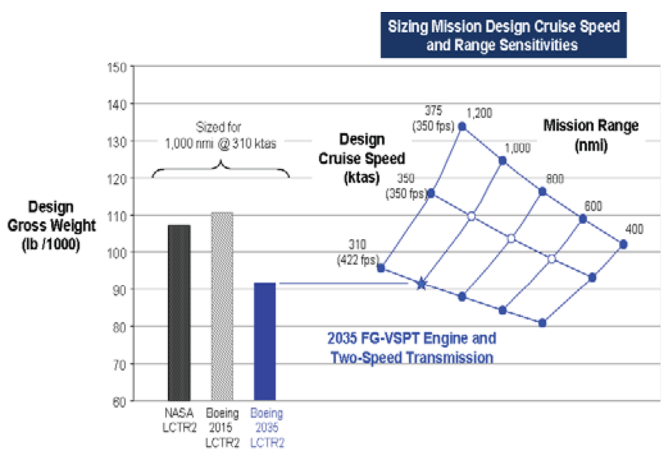

Figure 15: Design Gross Weight Sensitivity to Design Airspeed and Range

The accompanying bar chart on the left hand side of Figure 15 provides reference GW from three previous cases; the NASA LCTR2 design with 350 fps tip speed, the Boeing 2015 design with 500 fps tip speed, and the Boeing 2035 FG-VSPT design with 422 fps tip speed. The GW values displayed were the minimum GW for the selected tip speeds and propulsion system technology. Corresponding aircraft empty weight fractions (Empty Weight / GW) are shown in Figure 16. Higher design airspeeds require more installed SHP, heavier drive systems to deliver that power, as well as heavier rotors to provide increased thrust. All these lead to a higher empty weight fraction. Contrarily, at a given design airspeed, increased range requires more fuel, necessarily reducing the empty weight fraction to account for the added useful load (fuel).

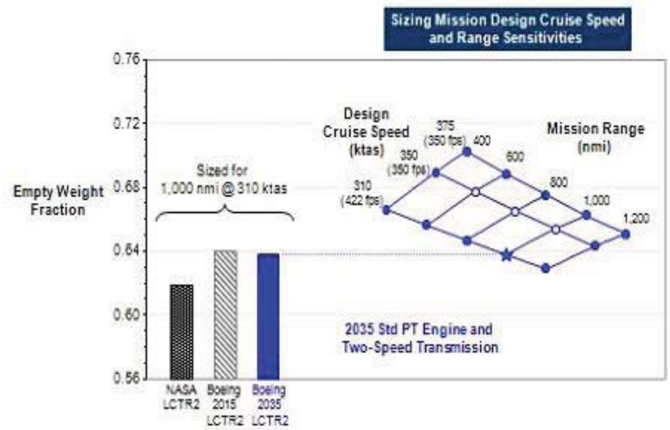

Figure 16: Aircraft Empty Weight Sensitivity to Design Airspeed and Range

Aircraft Operating Cost Variation with Design Airspeed and Range

Estimated values of DOC per flight hour (DOC/FH) and DOC/ASM are shown in Figure 17 for the same combinations of design airspeed and mission range shown above. These metrics have been normalized by PRICE results for the 2015 COTS engine at 100% rpm, 310 ktas and the 500 fps rotor tip speed. The 2035 drive system and FG-VSPT engine technology results in a reduced GW for the 310 ktas aircraft and reduced relative fuel flow/SHP. The relative DOC in Figure 17 for the 2035 engine and drive system technology shows that advanced technology can result in nearly 30% lower DOC/ASM and 20% lower DOC/FH relative to the best combination with 2015 technology.

DOC/FH naturally increases with aircraft GW; larger aircraft generally requiring more fuel per FH. But Figure 17 shows DOC/FH to be fairly flat with mission range for the 310 ktas design, even as GW grew from about 80,000 lb at the 400 nmi range up to 96,000 lb for the 1200 nmi range. That reflects the content of DOC/FH: part fuel costs that do increase with GW and part fixed costs per flight hour, such as crew salaries and expenses (overnight stays).

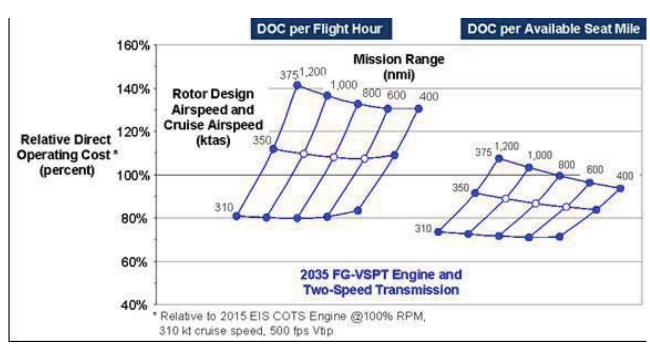

Figure 17: Relative Cost Variation with Design Airspeed and Range

Notably, DOC/FH increases significantly for design airspeeds of 350 ktas and 375 ktas driven by increased maintenance cost and fuel per FH associated with heavier, more powerful aircraft. DOC/FH shows more sensitivity to mission range at the higher cruise airspeed designs, presumably due to lower nmi/lb of fuel at the higher GW.

Results for DOC/FH and DOC/ASM reveal that the additional speed capability comes at a price, and there is no cost benefit for the additional airspeed even when considering the costs per seat mile, which is a measure of productivity scaled to transporting the individual customer.

Operating and support cost results (per flight hour) for 310 ktas sizing cases are presented in Figure 18 and Figure 19. The solid blue line represents the operating cost trend for 2 speed transmission sizing cases while the solid green line represents the engine based speed reduction cases. The dashed lines represent the GW variation for the same sizing cases and are proportionally scaled to the cost results. Trends show that there are minor differences in operating cost between an engine speed variant or a two speed transmission variant at higher cruise tip speeds of about 500fps and above. As the cruise tip speed takes a larger reduction toward 350fps, the operation cost favors a two speed gearbox rather than the engine based speed reduction. The relative cost minimum seems to coincide with lowest weight models for the vehicle, which is between 422 fps and 500 fps. Interestingly the cost model exhibits a greater variation between the two speed transmission trend and the engine based speed reduction trend than the GW trends indicate. GW variation at the minimum appears negligible while the operating cost advantage for a 2 speed system at the minimum design point is approximately 2.5%. This would be attributable to the greater fuel consumption for engine based speed reduction as indicated in Figure 14. Similar observations of the trends can be made for the operating cost per available seat mile chart of Figure 19.

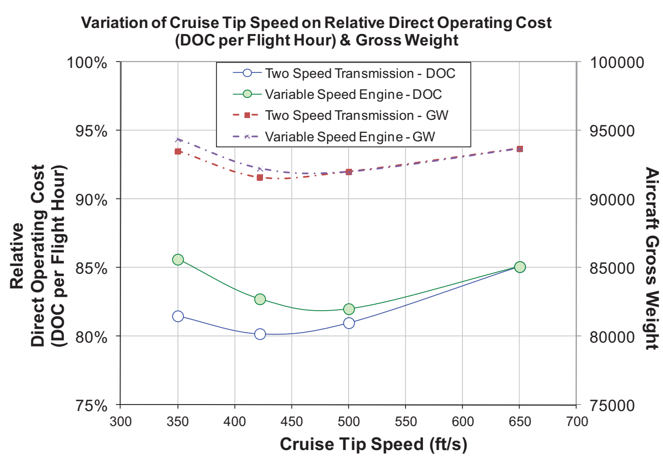

Figure 18: Operating Cost per FH at Various Cruise Tip Speeds at 310 ktas

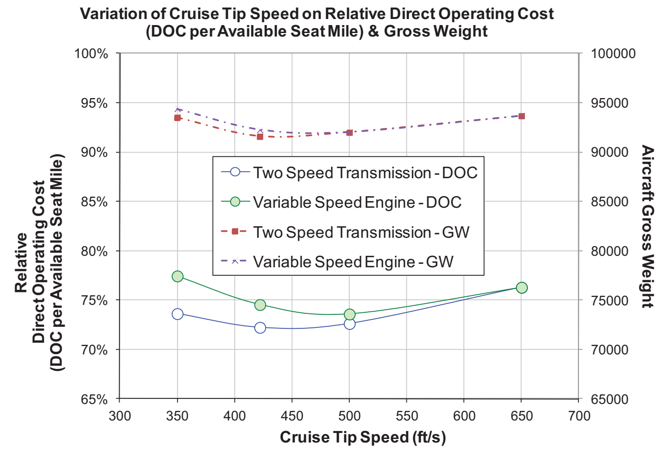

Figure 19: Operating Cost per ASM at Various Cruise Tip Speeds at 310 ktas

CONCLUSIONS

The 2035 FG-VSPT engine gave the lightest GW solution of the four engines evaluated, where the best rotor cruise tip speed was between 422 and 500 fps (65% and 77% of full rotor speed). This option had lower fuel flow and smaller engines (design SHP) than the 350 fps tip speed (54% rpm). Sizing analysis of the LCTR2 propulsion systems at the 422 fps rotor tip speed with the 2035 FG-VSPT engine and a two-speed drive system provided the lightest overall vehicle GW at 91,612 lbs. The 500 fps rotor tip speed produced a close second, 92,012 lb GW with either a single-speed or a 2-speed drive system. Reduced engine weight and fuel consumption associated with the 2035 FG-VSPT has a dramatic effect on vehicle sizing when compared to the COTS 2015 engine (best case) and represents a significant result in this study. A beneficial result in this study of the NASA LCTR2 design with a 350 fps tip speed is that it has investigated practical operational boundaries for a tiltrotor propulsion systems, as 422 to 500 fps tip speeds are far lower than the current V-22 cruise tip speed of 664 fps.

The LCTR2 GW weight differences between configurations that used engine based speed variation vs. drive system speed variation were subtle considering the significant variations studied in this effort. As an example, for the 422 fps sizing cases at the 2035 technology level, which represents the most favorable sizing cases in the study, the difference between two-speed transmission and reduced engine speed cases (91,612 lb and 92,260 lb respectively) is a mere 0.7%. For the 2015 technology level, the difference between two-speed and reduced engine speed for 500 fps best sizing is 0.4%. In general the two-speed transmission approach becomes more favorable where the engine performance falls off substantially, however the lower rotor speed cases where engine performance is diminished are not the optimum (lowest GW) configurations in this study.

The trade space examined in this study was heavily focused on vehicle sizing with the vehicle GW and system weights as the parameters of interest. A sensitivity study task was also conducted to evaluate weight trends and cost trends as mission range and speed were varied. Results are presented hold no surprises, the weight and cost of the LCTR2 vehicle rose predictably and proportionally as the variables of speed and range increased. It is notable however that operating costs favor a two speed transmission approach to speed reduction more distinctly than the GW analysis suggests. The most favorable operating costs for the 310 ktas cases examined were 2.5% better with the two speed approach as compared to engine based speed reduction due to differences in fuel consumption.

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14. ABSTRACT
In a series of study tasks conducted as a part of NASA's Fundamental Aeronautics Program, Rotary Wing Project, Boeing and Rolls-Royce explored propulsion, drive, and rotor system options for the NASA Large Civil TiltRotor (LCTR2) concept vehicle. The original objective of this study was to identify engine and drive system configurations to reduce rotor tip speed during cruise conditions and quantify the associated benefits. Previous NASA studies concluded that reducing rotor speed (from 650 fps hover tip speed) during cruise would reduce vehicle gross weight and fuel burn. Initially, rotor cruise speed ratios of 54 percent of the hover tip speed were of most interest during operation at cruise air speed of 310 ktas. Interim results were previously reported for cruise tip speed ratios of 100, 77, and 54 percent of the hover tip speed using engine and/or gearbox features to achieve the reduction. Technology levels from commercial off-the-shelf (COTS), through entry-in-service (EIS) dates of 2025 and 2035 were considered to assess the benefits of advanced technology on vehicle gross weight and fuel burn. This technical paper presents the final study results in terms of vehicle sizing and fuel burn as well as Operational and Support (O&S) costs. New vehicle sizing at rotor tip speed reduced to 65 percent of hover is presented for engine performance with an EIS 2035 fixed geometry variable speed power turbine. LCTR2 is also evaluated for missions range cases of 400, 600, 800, 1000, and 1200 nautical miles and cruise air speeds of 310, 350 and 375 ktas.

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