NASA/CR—2014-216661

Engine Power Turbine and Propulsion Pod Arrangement Study

Mark Robuck and Yiyi Zhang
The Boeing Company, Philadelphia, Pennsylvania

June 2014

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Engine Power Turbine and Propulsion Pod Arrangement Study

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Abstract

A study has been conducted for NASA Glenn Research Center under contract NNC10BA05B, Task NNC11TA80T to identify beneficial arrangements of the turboshaft engine, transmissions and related systems within the propulsion pod nacelle of NASA's Large Civil Tilt-Rotor 2nd iteration (LCTR2) vehicle. Propulsion pod layouts were used to investigate potential advantages, disadvantages, as well as constraints of various arrangements assuming front or aft shafted engines.

Results from previous NASA LCTR2 propulsion system studies and tasks performed by Boeing under NASA contracts are used as the basis for this study. This configuration consists of two Fixed Geometry Variable Speed Power Turbine Engines and related drive and rotor systems (per nacelle) arranged in tilting nacelles near the wing tip. Entry-into-service (EIS) 2035 technology is assumed for both the engine and drive systems. The variable speed rotor system changes from 100 percent speed for hover to 54 percent speed for cruise by the means of a two speed gearbox concept developed under previous NASA contracts. Propulsion and drive system configurations that resulted in minimum vehicle gross weight were identified in previous work and used here.

Results reported in this study illustrate that a forward shafted engine has a slight weight benefit over an aft shafted engine for the LCTR2 vehicle. Although the aft shafted engines provide a more controlled and centered CG (between hover and cruise), the length of the long rotor shaft and complicated engine exhaust arrangement outweighed the potential benefits.

A Multi-Disciplinary Analysis and Optimization (MDAO) approach for transmission sizing was also explored for this study. This tool offers quick analysis of gear loads, bearing lives, efficiencies, etc., through use of commercially available RomaxDESIGNER software. The goal was to create quick methods to explore various concept models. The output results from RomaxDESIGNER have been successfully linked to Boeing spreadsheets that generate gear tooth geometry in Catia 3D environment. Another initial goal was to link information from RomaxDESIGNER (such as hp, rpm, gear ratio) to populate Boeing's parametric weight spreadsheet and create an automated method to estimate drive system weight. This was only partially achieved due to the variety of weight models, number of manual inputs, and qualitative assessments required. A simplified weight spreadsheet was used with data inputs from RomaxDESIGNER along with manual inputs to perform rough weight calculations.

List of Symbols and Acronyms

AEO	all engines operating
CAD	computer aided design
CG	center of gravity
EIS	entry in service date
FG-VSPT	Fixed Geometry Variable Speed Power Turbine
fps	feet per second
hp	horsepower
IR	infrared
IRS	IR suppressors
ISA	International Standard Atmosphere
LCTR	Large Civil Tilt Rotor

LCTR2	Large Civil Tilt Rotor 2nd Iteration
LH	left hand
LRU	Line Removable Unit
MCP	Maximum Continous Power
MDAO	Multi-Disciplinary Analysis and Optimization
n mi	nautical miles
OD	outer diameter
OEI	One Engine Inoperative
RH	right hand
rpm	revolutions per minute
RTAPS	Research and Technology for Aerospace Propulsion Systems
VAATE	Versatile Affordable Advanced Turbine Engines
WBS	Work Breakdown Structure

1.0 Introduction

Tilt-rotor aircraft offer the capability of vertical take-off and landing in the helicopter mode as well as the ability to perform high speed and long endurance missions as an airplane. The Bell-Boeing V-22 Osprey, as an example, has brought new capabilities to the war fighters. Typical for a tilt-rotor, the V-22 operates with a higher rotor speed for hover and reduces to a lower rotor speed for cruising with nacelles tilted to a forward position. Tilt-rotor vehicles have been studied by NASA for commercial use as a solution for overloaded airport infrastructure. The concept for a Large Civil Tilt-rotor (LCTR) has evolved through various NASA studies and projects since year 2000. This project focuses on the 2nd iteration of the aircraft, known as LCTR2 (see Figure 1). It is sized to carry 90 passengers and baggage (19,800 lb). The vehicle take off gross weight is approximately 107,700 lb.

Boeing had performed studies for NASA focused on sizing the LCTR2 propulsion system for reduced total aircraft gross weight and performance. These efforts are described in technical papers (Refs. 1, 2, and 3). The primary goal of the current study and subject of the report is to use propulsion system concepts and sizing parameters generated in the previous work to develop nacelle conceptual layouts for the LCTR2 assuming notional front or aft drive turbine engines. This study explores the advantages and disadvantages of front/aft drive engines in terms of nacelle (propulsion pod) layout space and weight. In addition, a Multi-Disciplinary Analysis and Optimization (MDAO) tool is also developed and used to analyze various transmission concepts. This approach provides the designer with the capability to create a more immediate assessment of weights, gear sizing, shaft analysis, etc., to build a concept transmission gearbox.

In previous study projects, Boeing explored rotor speed reductions from 100 percent down to 54 percent of LCTR2 hover rpm as well as various engine and drive system configuration at three different technology levels. Results from these studies provided the sizing parameters for this effort and the general architecture for the propulsion system. The selected engine from that study was a Rolls-Royce Fixed Geometry Variable Speed Power Turbine (FG-VSPT) engine designated PD628 as described in the referenced VSPT paper (Ref. 4). This engine is the baseline engine for the current study and is paired with rotor transmissions that feature two speed gearbox modules to reduce the rotor speed to 54 percent of hover rotor rpm for cruise conditions. A variation to the PD628 3-spool front-shafted engine is considered in this project. An aft shafted engine configuration is included as a variation in this study to explore nacelle packaging attributes and other potential benefits. The aft shafted engine would reduce the design complexity expected with the forward shafted engine, which uses three concentric shafts within a small engine and as a result, could have negative effects on turbomachinery and overall engine design and performance. An aft shafted engine may alleviate shafting issues within the engine, and is expected to have a weight benefit for the engine, although engine exhaust ducting is more complicated. Details of the engine internal arrangements are only briefly presented in this study.

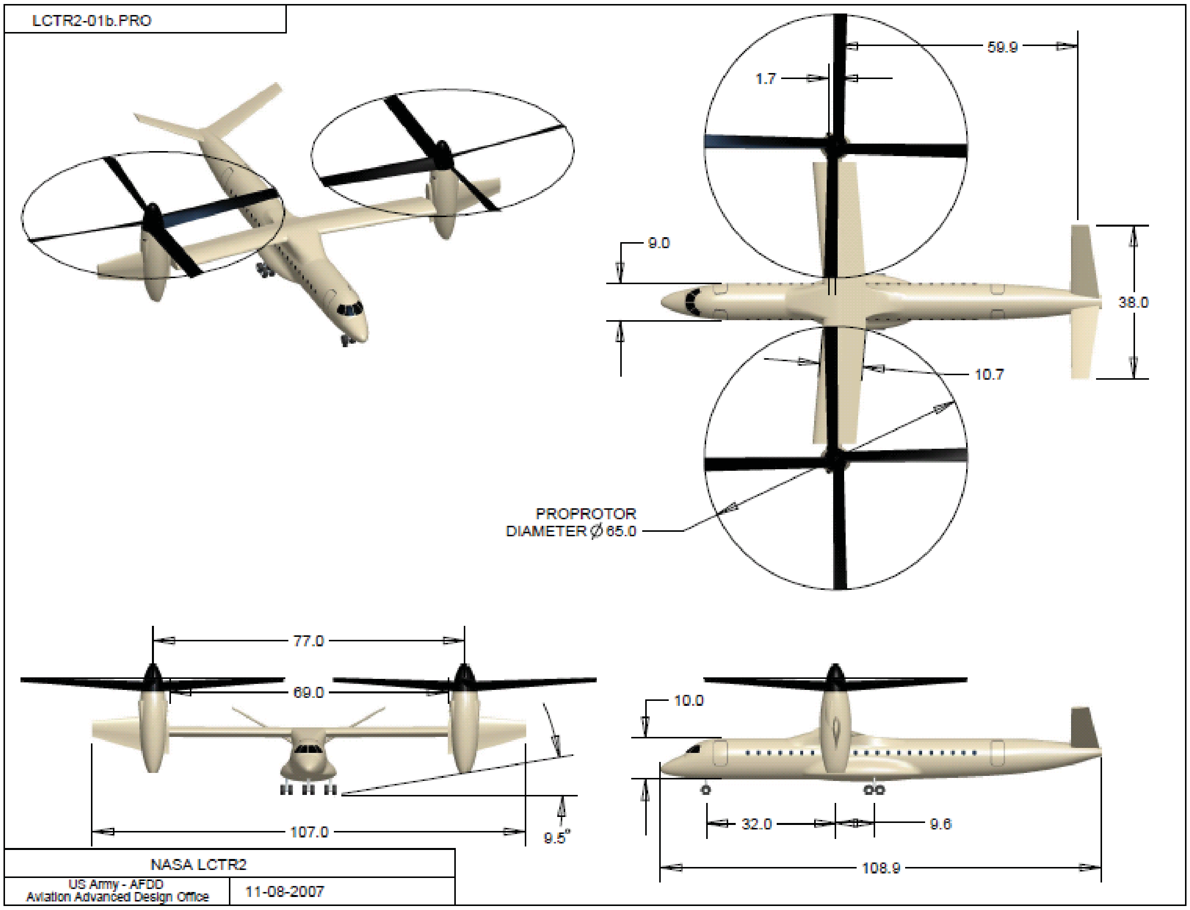

Figure 1.—LCTR2 Vehicle.

1.1 Background

NASA had awarded Boeing with contracts (NNA06BC41C and NNA09DA56C) to perform limited trade studies for propulsion system effects on vehicle sizing for the LCTR2. The investigation focused on identifying the most advantageous speed variation concepts to provide an optimized propulsion system and lightest weight vehicle sizing. The original NASA design point suggested that vehicle performance is optimized for cruise with the rotor speed at 50 percent of hover rotor speed. The lightest solution according to Boeing's analyses resulted between 65 to 77 percent of hover speed. Results from these studies were reported in a final report presented to NASA entitled "The Effect of Rotor Cruise Tip Speed, Engine Technology and Engine/Drive System rpm on the NASA Large Civil Tilt-rotor (LCTR2) Size and Performance," (Ref. 4) and References 1, 2, and 3. These results and original design constraints are partially presented here as description of the ground rules and assumptions.

1.2 Tasks

This report summarizes efforts and accomplishments completed under NASA Contract NNC10BA05B (Research and Technology for Aerospace Propulsion Systems (RTAPS)) entitled "Engine Power Turbine and Propulsion Pod Arrangement Study". This project is divided into two segments. The first segment of the project (Base project) focuses on developing conceptual layouts and spatial arrangements for the LCTR2 vehicle nacelle propulsion pod. The second segment (Options project) involves creating the MDAO tool to perform rapid iterations and evaluations of concept drive system configurations. The descriptions of the tasks are detailed in Appendix A.

The Base project creates various layouts of the transmissions arranged within the nacelle pod as necessary to interface with a notional front or aft-drive turbine engine. The goal of the project is to determine the size and location of the transmission components in the nacelle and to identify which engine installation provides the optimum design for LCTR2. Factors that affect layout arrangement include engine shaft location, rotor shaft sizing, CG effects, weight, etc. Key technical challenges for each layout are presented. Benefits of a front shafted or aft shafted engine are also explored.

The Options project consists of developing a drive system MDAO approach and using it to analyze the layout for the Base project. For a typical transmission design, information such as weight, component sizing, stress analysis and bearing lives are normally needed to select the preferred layout for a vehicle. The MDAO approach is based on commercially available software (RomaxDESIGNER) and Boeing's own parametric spreadsheets. Two spreadsheets to be integrated are (1) Parametric Weights Spreadsheet and (2) a gear profile generator for 3D Catia models. The MDAO tool is setup so that the user would be able to quickly analyze various transmission concepts.

2.0 Technical Approach

2.1 NASA LCTR2 Design Parameters

The transmission systems are (conceptually) designed based on results obtained from previous projects and parameters such as vehicle configuration, operating conditions, and mission assumptions that are consistent with the LCTR2 concept. The original LCTR2 configuration provided by NASA is based on four 7500 hp engines with two at each nacelle. Boeing's previous studies refined the power requirement to approximately 6400 hp (see Table 1). The selected tip speed is 650 fps for hover and 350 fps for cruise mode (54 percent of hover speed). Cruise condition occurs at 310 kn at an altitude of 25,000 ft for a nominal mission of 1,000 n mi.

The mission profile is shown in Figure 2. The LCTR2 mission is cruise-dominated. It is very similar to regional aircraft except for the vehicle vertical takeoff and landing portions. Transition from vertical take-off to airplane mode is followed by a rotor speed change to the cruise rotor speed which occurs early in the climb segment of this profile. The reduction in rotor speed is achieved by utilizing four speed changer gearboxes (one at each engine). All engine and drive system components are assumed to retain the technology advances for EIS 2035. NASA also provided envelope sizing for the nacelle:

Nacelle (NASA supplied info based on 7700 hp engine):

- Nacelle Geometry:
    - Max Diameter: 27 in

TABLE 1.—DRIVE SYSTEM DESIGN TABLE

Ratings	Input shaft (engine) (3)			Output shaft (prop rotor shaft) (2)			Output to wing interconnect shaft (1)		
	hp	rpm	Torque, in.-lb	hp	rpm	Torque, in.-lb	hp	rpm	Torque, in.-lb
Nominal AEO hover rating	4,432	15,000	18,620	8,125	200	2,558,187	800	8,041	6,270
Nominal AEO cruise (airplane) rating	2,749	15,000	11,549	5,933	108	3,469,591	800	4,390	11,485
Nominal OEI hover rating	5,318	15,000	22,344	7,617	200	2,400,218	2,659	8,041	20,840
Nominal OEI cruise (airplane) rating	3,298	15,000	13,859	4,588	108	2,677,209	1,649	4,390	23,677
Max AEO hover rating	5,539	15,000	23,275	9,749	200	3,069,824	3,545	8,041	27,787
Max AEO cruise (airplane) rating	3,436	15,000	14,436	5,933	108	3,469,591	2,199	4,390	31,569
Max OEI hover rating	6,381	15,000	26,812	7,617	200	2,400,218	4,254	8,041	33,345
Max OEI cruise (airplane) rating	3,958	15,000	16,631	4,588	108	2,677,209	2,639	4,390	37,883

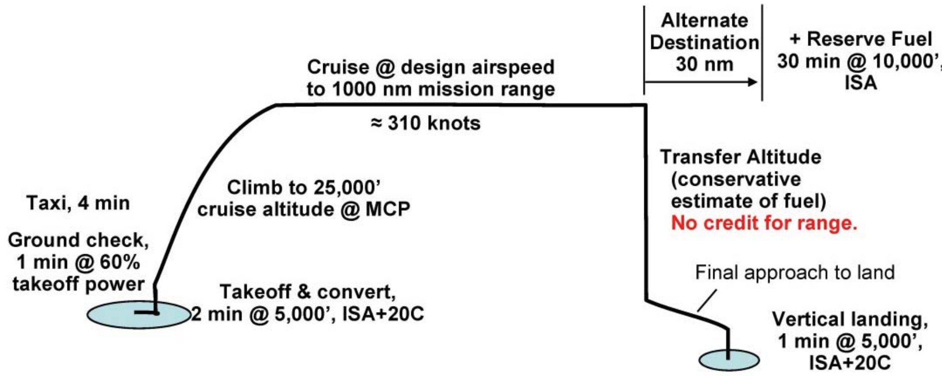

Figure 2.—NASA Mission Profile for LCTR2 Study.

The engine selected from the previous studies is Rolls-Royce's FG-VSPT (concept) engine designated as PD628, with technology features from the Versatile Affordable Advanced Turbine Engine (VAATE) engine program. Engine design includes a three stage power turbine optimized for operation around 90 to 100 percent rpm and some capability outside this range attributed to variable incidence angle airfoils. Using the VSPT research (Ref. 5), Rolls-Royce generated engine performance data for this project assuming VSPT technology optimized around 90 percent rpm. This EIS 2035 FG-VSPT design includes an extra power turbine stage that was used in the overall design to improve performance and operability over the variable speed range with only minimal additional weight and complexity. The engines are sized for One Engine Inoperative (OEI) condition with the following assumptions:

- Rolls-Royce PD628 engine with EIS 2035 VAATE technologies.
- Air vehicle accessory power assumed to be 800 hp drawn at mid-wing accessory gearbox.
- Rotor to rotor torque split: 60/40 distribution
- Engine to engine power distribution factor: additional 5 percent
- Engine geometry (Rolls-Royce)
    - Diameter: 24.4 in.
    - Length
        - 62 in. (inlet flange to exit flange)
        - 81 in. (including output shaft)
            - Engine weight: 807 lb (Weight scaled from Rolls-Royce data)

The overall drive system layout is illustrated in Figure 3, which is similar to the V-22 layout with the addition of speed changer gearboxes and two engines at each nacelle. It consists of five transmissions: left hand (LH) proprotor, right hand (RH) proprotor, tilt axis, and a mid-wing gearbox (MWGB). They were established in the previous studies and carried over for this study. Drive System assumptions are listed below:

- Based on LCTR2 architecture and V-22 mechanical features, a Helical Idler geartrain is used to transfer power from engines to Bull Gear, Planetary Systems, and Rotor Shaft.
- Sized by OEI power requirements (approximately 6400 hp for hover and 4000 hp for cruise). The remaining three engines are to provide 90 percent of normal power rating with a distribution factor of 1.2.
- Desired location of Speed Changing module is in the high speed portion of the drive train near the engines to minimize weight and provide redundancy that may reduce sub-system criticality.
- Two speed gearbox speed changer is 17-in. in diameter and 21-in. long from previous sizing analysis.
- Weight analysis for the full drivetrain is based on Boeing weight trend analysis.

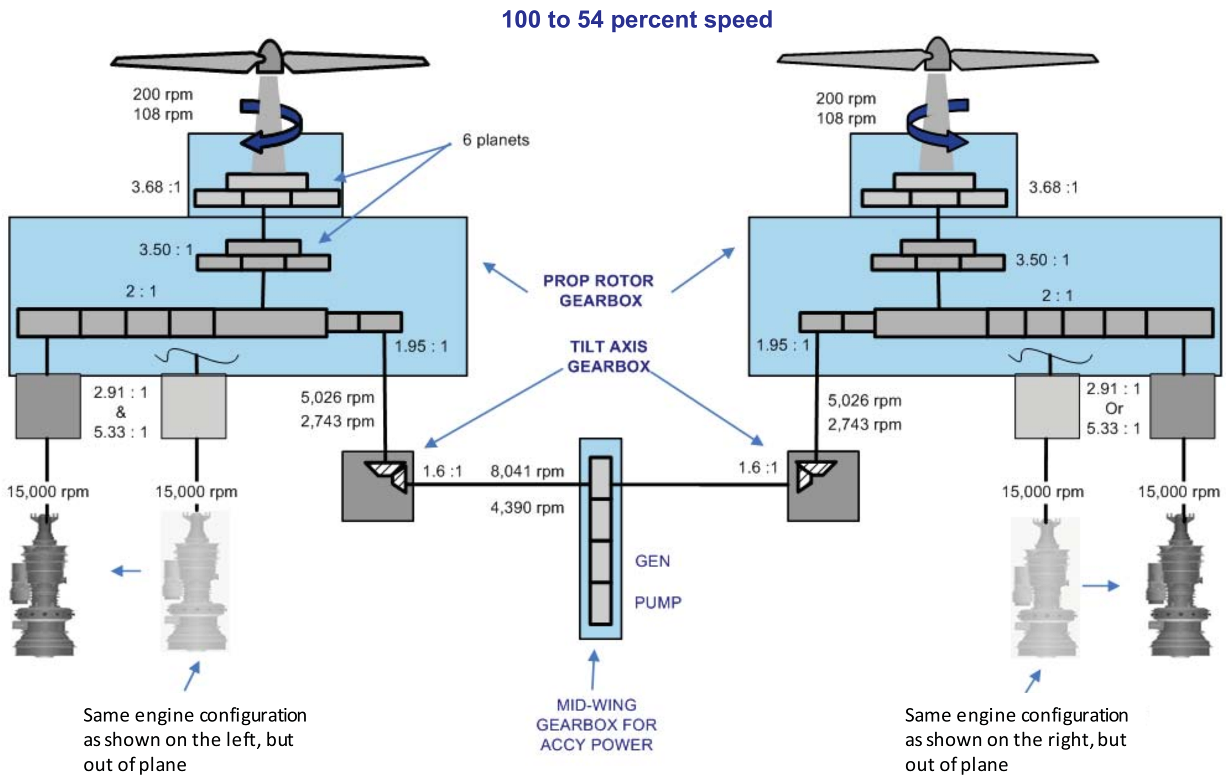

Figure 3.—LCTR2 Drive System Baseline Schematic Layout Option 1.

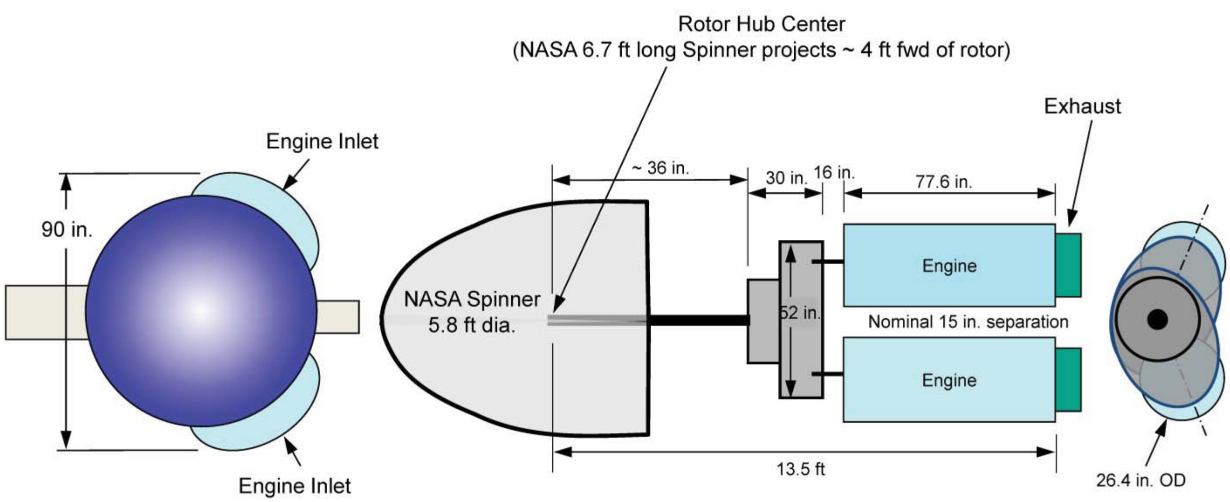

Figure 4.—Nacelle layout (approximate dimensions).

2.2 Base Project: Propulsion Pod Layout

The RTAPS LCTR2 Propulsion Pod Layout Base Project was established to study the spatial arrangement of propulsion system components within the LCTR2 nacelles with a specific goal to explore forward and aft (output) shafted engines. Integration of engine and drive system space allocations within the nacelle are affected by gearbox and engine configurations, as well as numerous other considerations including inlet and exhaust requirements, structural components, nacelle size, etc. The placement of these components also affects the CG of the aircraft. Rough initial component positions are shown in Figure 4 (results from previous work).

Space models of the drive system components are modeled in the 3D environment using Catia CAD software from Dassault Systems. Space allocation models are established for individual nacelle components and assembled together. 3D models provide an easy visualization of component relative sizing and installation space and offer a clear view of space allocation issues. Gear sizes were used to establish the transmission volume for each location. Gears in the main gearbox are roughly sized by Boeing's Gear Technology group using commercially available software 'Powergear' developed by Drive System Technology, Inc. and subsequently modeled using 'RomaxDESIGNER'.

This study explores how nacelle space allocations are affected by front versus aft shafted engines and associated drive system options. Typically, the drive system interfaces directly at the front of the engine output shaft; therefore, forward driven engines would need a shorter rotor shaft to reach the hub whereas an aft driven engine arrangement would require a much longer rotor shaft to reach the rotor hub. The two engine types also affect the inlet/exhaust for the engine. With the drive systems located directly in front of the engine shaft, the inlet for a front shafted engine sweeps around the engine shaft into a volute shape to provide airflow to the engine. Aft shafted engine offers a clear opening for engine inlet, but the exhaust ducting becomes more complicated as it needs to clear the aft engine shaft as well as the gearbox.

The LCTR2 is a tilt-rotor vehicle that converts from helicopter to airplane mode and vice versa by rotating the nacelles from vertical to horizontal orientation (see Figure 5). As the nacelle rotates, the CG of the aircraft shifts as the unbalanced weight of the nacelle pivots about the nacelle tilt axis. This conversion can result in large moments and movement of the aircraft CG. Minimizing CG shift and weight is therefore one of the factors considered when allocating spaces for nacelle components.

Even though LCTR2 is a commercial aircraft, IR suppressors, exhaust cooling or diversion provisions are needed to manage the exhaust temperatures. To take off in hover mode, the engine expels exhaust directly downward toward the airport runway surface. IR provisions are necessary to reduce the heat of the exhaust plume and avoid damage to the tarmac during take-off and landing. In this study, details of this system are not explored however suppressor mass and volume are approximated from comparable production hardware and included in analysis and modeling.

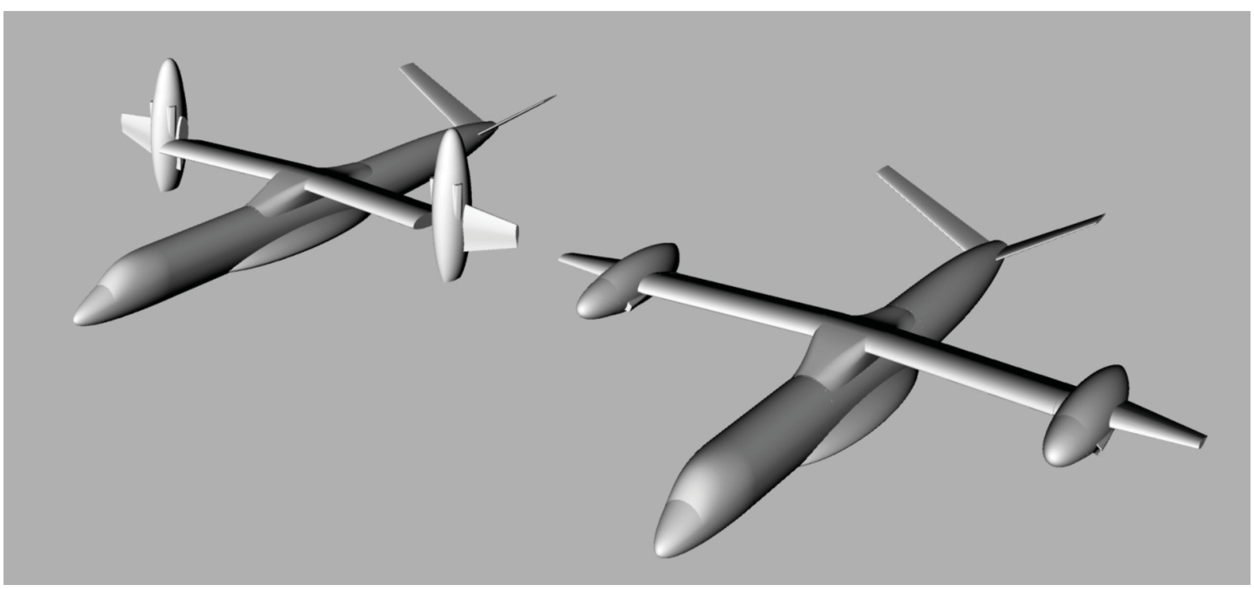

Figure 5.—NASA LCTR2 layout without rotors. (Provided by NASA.)

2.3 Options Project: MDAO Tool

As an option added to the original RTAPS project, Boeing proposed to develop tools and methodology for drive train weight analysis and optimization that occurs as a part of Concept Development/ Preliminary Design processes. The approach taken for this task is to construct a multi-disciplinary analysis and optimization (MDAO) environment for aerospace/rotorcraft gearbox analysis with overall benefits of rapid design iterations, shorter design/analysis cycle time and improved technical solutions. The MDAO gearbox design tool consists of commercially available transmission design software with customized worksheet add-ons. The expectation for this tool is to perform rapid iterations of configuration and operating conditions to reach an optimized design.

To select the best drive system solution for new vehicle designs, engineers typically explore envelope size, weight, and layout options for numerous configurations, which is a time-consuming process. The current conceptual/preliminary design process requires engineers to select configurations and combinations of gear sets to achieve the desire reduction ratio and evaluate weight using a parametric spreadsheet to find the lightest weight solution. The gear meshes are then sized using an analysis tool and are often modeled in the 3D environment to obtain calculated weight values for components such as gears, shafts, housings, and bearings. These steps are often repeated several times to reach an optimum design. Each step of the process is performed sequentially with various different resources and requires time to execute and to transfer the data from one group to another. The MDAO tool attempts to eliminate some of these processing steps and time by integrating three processes of developing a drive system: (1) Boeing's parametric weight's spreadsheet, (2) Boeing's parametric three-dimensional CAD spreadsheet, and (3) the gear/shaft and bearing design software (RomaxDESIGNER).

2.3.1 Weights Spreadsheet

Drive system weights make up significant portions of the overall rotary wing aircraft gross weight, generally between 10 to 15 percent. As engineers lay out various drive system combinations to provide power to the rotors and satisfy the vehicle requirements, it is very helpful to have early weight assessments. A parametric weight comparison of each layout during early conceptual design becomes crucial in down-selecting to a few possible light weight solutions for further detailed study. Boeing engineers have developed parametric tools and methods to predict the approximate weight of the gearboxes that allow for quick assessments at an early conceptual design stage.

The methodology used for drive system weights is described in the Society of Allied Weight Engineers (SAWE) papers (Refs. 6 and 7). This methodology is particularly useful in the early stages of design because it predicts system level weight for transmissions and shafts from basic information. According to the papers, the standard deviation for the accuracy of the calculated weights versus actual weights is ±9.3 percent with a correlation coefficient of 0.998. Over time, Boeing Weights Engineers have further refined the procedure with legacy data and extensive application of the method, which utilizes readily available information such as surface compressive stress index, design horsepower, input speeds, reduction ratios, etc., to determine the approximate weight of the gearbox or drive system. Predictions from the parametric weights spreadsheet have proven to be very close to actual aircraft weight. Data can be extracted from the RomaxDESIGNER models to provide the design parameters to the weights spreadsheet, and quickly establish system level weights analysis using initial concept level design information and trend analysis from industry experience.

2.3.2 Parametric Catia Models

Computer Aided Design (CAD) information in the form of 3D solids is the accepted norm for mechanical system design by providing the basis for analysis, (specific) manufacturing processes, inspection, etc. CAD models (Catia) of mechanical transmission components generally require significant schedule and budget to generate. With each design, unique models are required to build a gearbox, often numbering over 100 components per transmission. For a concept or preliminary design study, quick methods of creating components in the CAD environment are beneficial for defining the size and

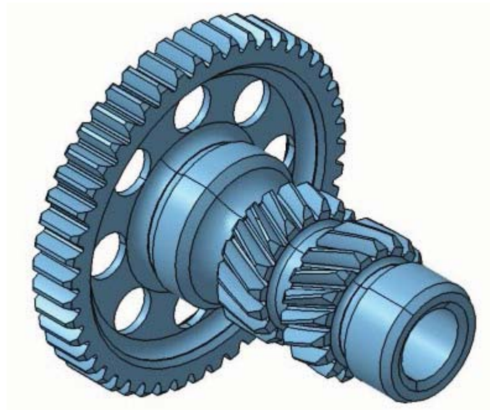

Figure 6.—LCTR2 Speed Changer Planet Gear.

arrangement early in the design phase. Boeing had previously created parametric CAD models for gears using a Microsoft Excel spreadsheet to input the parameters. In this activity, similar spreadsheets are linked to RomaxDESIGNER design/analysis models and to the CAD system so that it will generate basic and raw gear component models required to define and assemble a gearbox in the CAD design system. Figure 6 is a component model that is a product of this spreadsheet process.

Information required to create the CAD spreadsheet and related Catia 3D solid are easily accessible from the RomaxDESIGNER models. Basic gear geometries such as pitch diameter, tooth number, pressure angle, tooth width, etc., are extracted from RomaxDESIGNER and stored in the spreadsheet. Each gear is generated by its corresponding spreadsheet with a common integrated shaft connecting the gears together as one component. Once the spreadsheets are linked to the Catia model, updates to the gear geometry that are entered into the spreadsheet automatically update the CAD models accordingly. This project reduces the manual transcription of data and shortens the design cycle by automatically feeding updated geometry to the Excel spreadsheet.

2.3.3 RomaxDESIGNER Software

The RomaxDESIGNER software is developed by Romax Technology. The software provides high accuracy analysis and simulation of gears, bearings, shafts, and driveline systems in assembly. It provides information such as component weights, stresses, forces, deflections, component lives, etc. The RomaxDESIGNER software also provides methods to optimize system performance and assess dynamic behaviors of systems in the early stage of the design cycle. It creates 3D images for visual effects and interpretation (see Figure 7), and provides analysis results for sizing and layout (see sample results in Table 2). Currently, it is most commonly used in the automobile and wind energy industries.

Both input and results from RomaxDESIGNER can be exported as XML files allowing users to extract data for usage in other programs and analysis. In this project, information related to weights (such as horsepower, torque, gear ratios) and gear geometry (such as pitch diameter, tooth width, number of teeth) are extracted from the XML file and imported to Excel spreadsheets. Since the XML files from RomaxDESIGNER are specified in metric units, unit conversions are imbedded in the Excel macro as well. RomaxDESIGNER software does provide a weight calculation of the rotating components as a part of the analysis, but cannot calculate a full drive system weight, since that is dependent on many factors outside the scope of the RomaxDESIGNER analysis, i.e., lube system weight, housing structural considerations, etc.

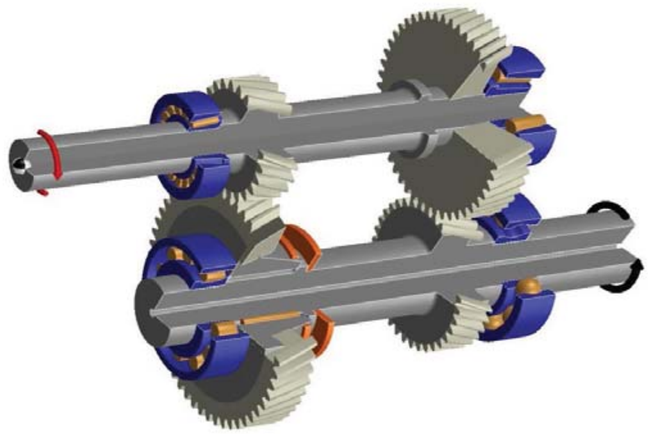

Figure 7.—Sample RomaxDESIGNER Design (Source: Romax Technology Website, used with permission).

TABLE 2.—SAMPLE RomaxDESIGNER RESULTS OUTPUT FOR SHAFTS

(a) Forces

Node	Offset, mm	X applied, N	X reaction, N	Y applied, N	Y reaction, N	Z applied, N	Z reaction, N	Radial applied, N	Radial reaction, N	XZ, N	YZ, N
1	0	0	0	0	0	0	0	0	0	0	0
2	10.000	0	0	0	0	0	0	0	0	0	0
3	34.167	0	0	0	0	0	0	0	0	0	0
4	58.333	0	0	0	0	0	0	0	0	0	0
5	82.500	0	–11792.7	0	3668.0	0	3403.3	0	12350.0	–11792.7	3668.0

(b) Moments

Node	Offset, mm	About X applied, N mi	About X reaction, N mi	About Y applied, N mi	About Y reaction, N mi	About Z applied, N mi	About Z reaction, N mi	XZ right, N mi	XZ left, N mi	YZ right, N mi	YZ right, N mi
1	0	0	0	0	0	0	0	0	0	0	0
2	10.000	0	0	0	0	400	0	0	0	0	0
3	34.167	0	0	0	0	0	0	0	0	0	0
4	58.333	0	0	0	0	0	0	0	0	0	0
5	82.500	0	–15.1378	0	–44.0148	0	0	0	–44.0148	0	–15.1378

(c) Displacement

Node	Offset, mm	Radial, μm	X, μm	Y, μm	Z, μm	Slope about X, mrad	Slope about Y, mrad	Twist about Z, mrad
1	0	63.40	–19.26	60.41	86.82	0.85676	0.72011	45.839
2	10.000	53.23	–12.06	51.84	86.82	0.85676	0.72011	45.839
3	34.167	31.59	5.34	31.14	86.82	0.85676	0.72011	45.839
4	58.333	25.02	22.75	10.43	86.82	0.85676	0.72011	39.556
5	82.500	41.44	40.15	–10.27	86.82	0.85676	0.72011	36.414

(d) Stresses

Node	Offset, mm	Bending left, MPa	Bending right, MPa	Tension left, MPa	Tension right, MPa	Torsion left, MPa	Torsion right, MPa
1	0	0	0	0	0	0	0
2	10.000	0	0	0	0	0	130.3797
3	34.167	0	0	0	0	130.3797	130.3797
4	58.333	0	0	0	0	130.3797	130.3797
5	82.500	0	30.3427	0	–6.9330	130.3797	130.3797

3.0 Nacelle Pod Arrangements

3.1 Layout Options

3.1.1 Drive System Layout Options

From the baseline drive system layout established in a prior LCTR2 study project (Ref. 1 to 3) as shown in Figure 3, numerous additional concept variations were explored in this project. Alternate drive system configurations were included to evaluate forward versus aft shafted engine configurations, as well as gearbox final drive options such as compound planetary versus split torque versus traditional (dual) simple planetary output stages. The location and configuration of the speed changer module was also re-examined to provide an unobstructed engine inlet, and take advantage of a perceived weight reduction.

As shown below, the location of the speed changer gearbox is the major difference between Figure 3 (Option 1) and Figure 8 (Option 2). With a 17-in. outside diameter, the speed changer could obstruct the engine inlet. A lighter drive system is expected by relocating the speed changer further down the drive train and closer to the bull gear. The idlers are now operating at a higher speed and lower torque and space conflicts with the engine inlet are also alleviated.

In the course of the design study, Options 3, 3A, and 4 also emerged as possible solutions. These additional drive system layout options replaced the final reduction stage (simple planetary output) with compound planetary systems and split torque arrangement, respectively. Parametric weights were analyzed for each configuration (see Table 3) for comparison. The table shows that there is significant weight benefit to change the final stage output. However, there's not enough weight discrepancy between compound planetary and split torque arrangement; therefore, both was carried forward in the study.

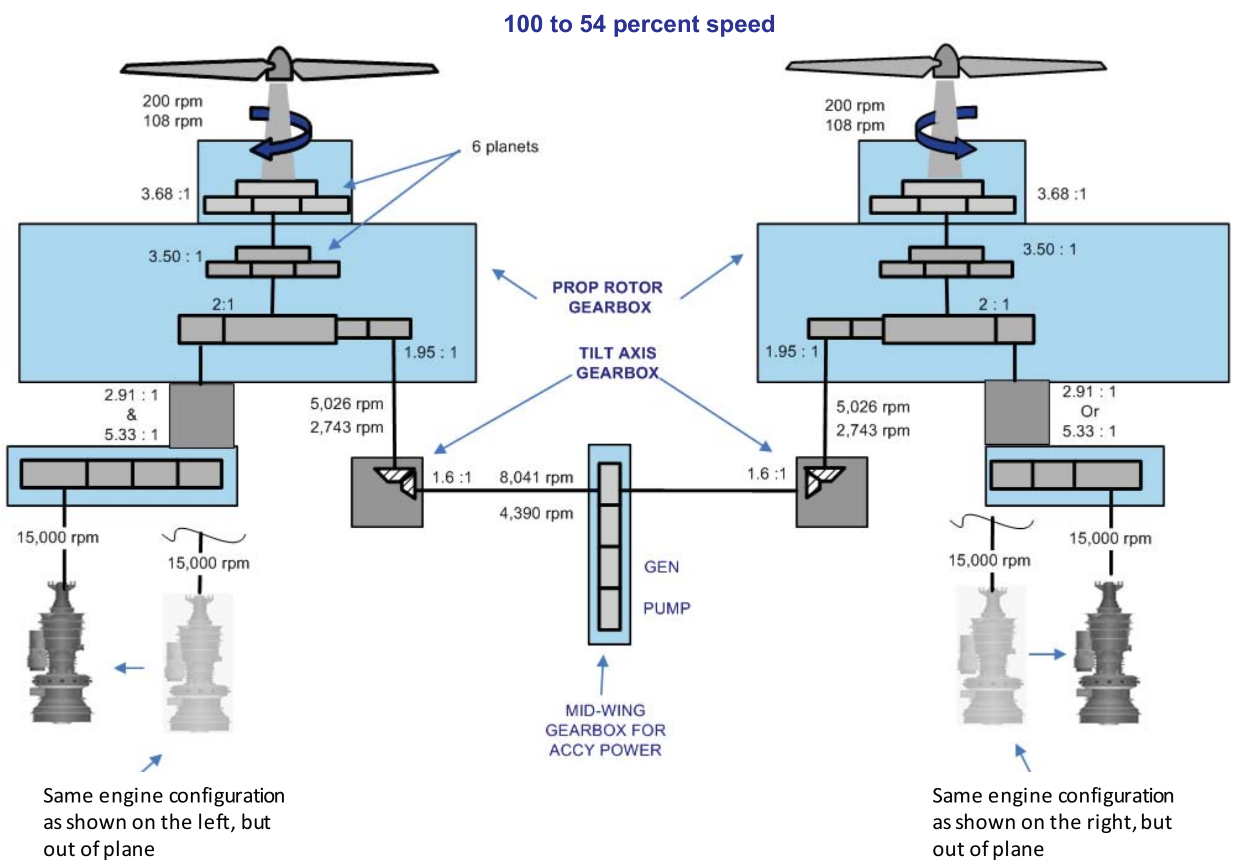

Figure 8.—Drive System Layout Option 2 (Dual Planetary System).

Parametric weight in Table 3 shows that Option 3 (Figure 9) offers the lightest weight solution. The speed changer relocation was retained from Option 2. However, relocating the speed changer further down the drive train between gearbox sections made maintenance difficult for the speed changer gearbox. Portions of the Prop Rotor Gearbox assembly would need to be removed in order to disassemble the speed changer from the drive train for servicing. Since the speed changer has a high part count and employs friction clutches, a higher frequency maintenance schedule is expected; therefore the speed changer was pulled out of the assembly and configured as a separate bolt on Line Removable Unit (LRU) for easier maintenance (see Figure 10). This configuration (3A) is slightly heavier than configuration 3, but much more desirable for servicing.

TABLE 3.—PARAMETRIC DRIVE SYSTEM WEIGHT

Configuration	Weight, lb
Option 1 (Dual Planetary)	8516
Option 2 (Dual Planetary)	7747
Option 3 (Compound Planetary)	7435
Option 3a (Compound Planetary)	7463
Option 4 (Split Torque)	7673

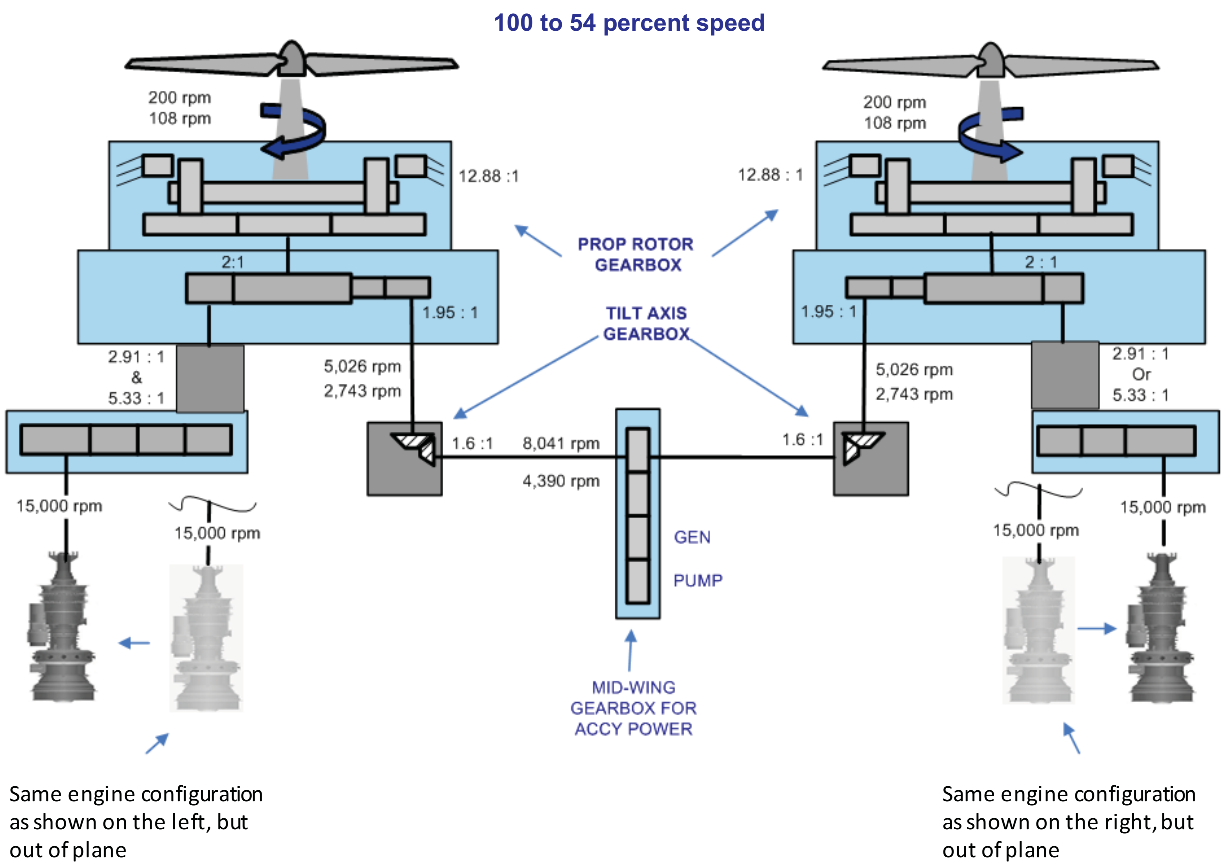

Figure 9.—Drive System Layout Option 3 (Compound Planetary System).

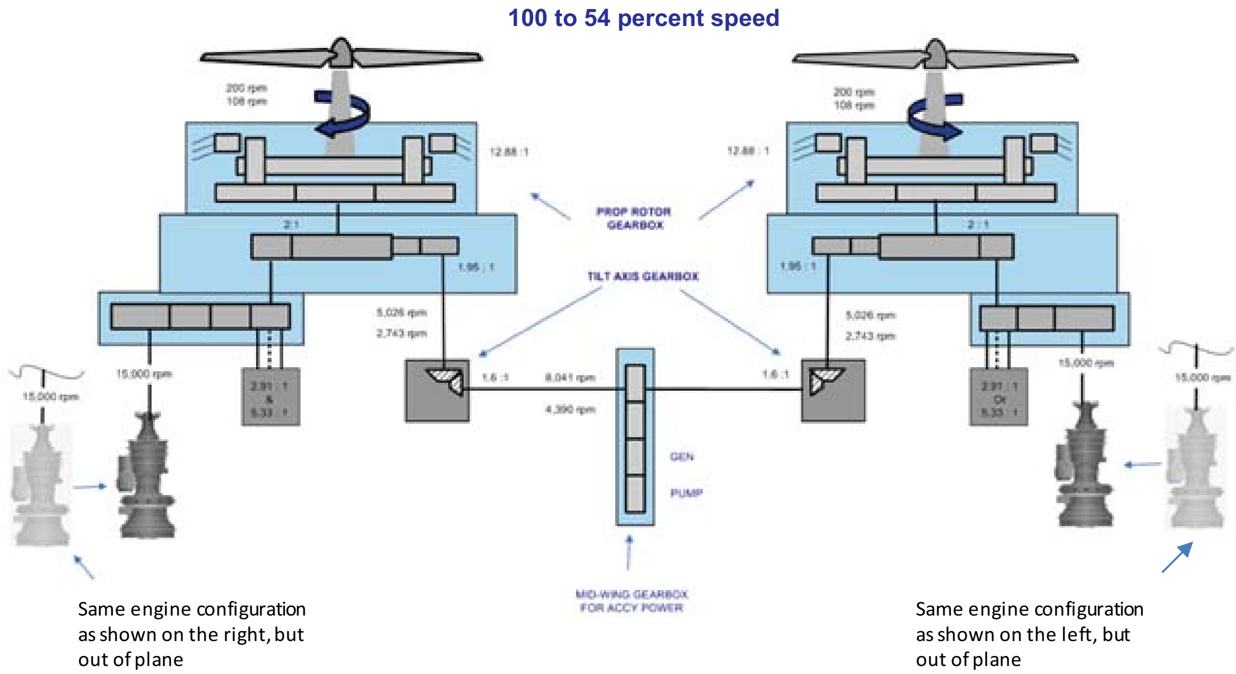

Figure 10.—Drive System Layout Option 3a (Compound Planetary System).

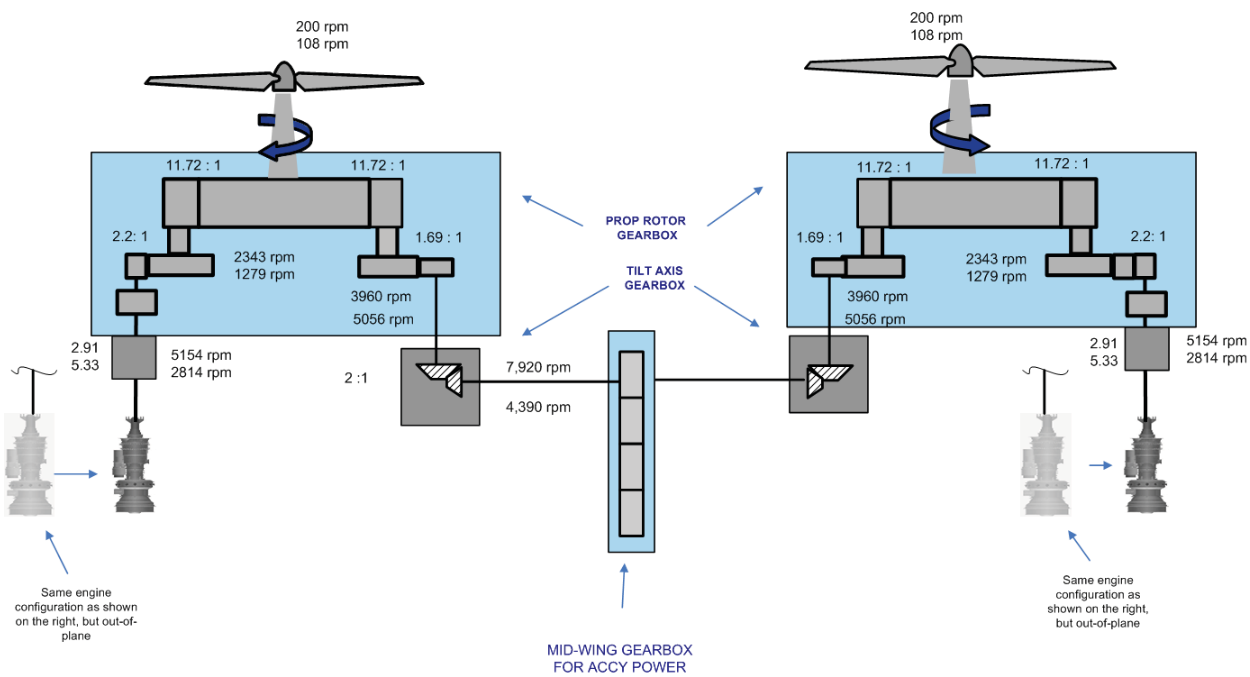

Figure 11.—Drive System Layout Option 4 (Split Torque System).

The split torque arrangement (see Figure 11) is similar to Sikorsky's CH-53K transmission layout (Ref. 8). There are two reduction stages for this portion of drive system. The first reduction in the PRGB is the input gear shaft in mesh with four gears (Figure 12). The second stage gears are meshing to a bull gear which provides the output to the rotor. For this configuration, the speed changer can only be located directly at the engine input and functions as the initial reduction stage. This arrangement is lighter than the dual planetary concepts and only slightly heavier than the compound planetary systems.

3.1.2 Forward Drive Versus Aft Drive Engine

The NASA LCTR2 concept vehicle is configured with four engines, two located at each (tilting) nacelle. As established in previous work, these two engines are placed one above another. Options 3a and 4 are selected for further evaluation in this portion of the study, since they were assessed as the lightest weight drive system options according to Boeing’s parametric weight trends. These two configuration options are paired with two types of engines, forward shafted and aft shafted engines. Approximate locations of major components in the nacelle, such as rotor placement, swashplate, tilt-axis spindle, engines, speed changer, IR suppressors, etc., are arranged in 3D with rough envelope sizing.

Figure 13 shows the nacelle arrangement with Option 3a drive system layout paired with a forward shafted engine. In this arrangement, the engine plugs right into the drive train. As discussed earlier, the location of the speed changer offers a clear engine inlet pathway for air flow as well as easy access for servicing. Ducting for outlet air is also simple when compared to other layouts. However, this arrangement does not offer a good balance for the nacelle. Heavy components, such as the rotor and drive system, are placed in front of the tilting nacelle, with the engines acting as the only main balance aft of the tilt axis.

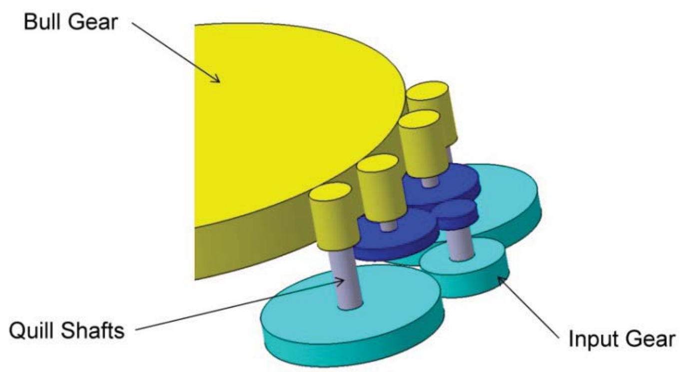

Figure 12.—Option 4—Split Torque Arrangement in 3D.

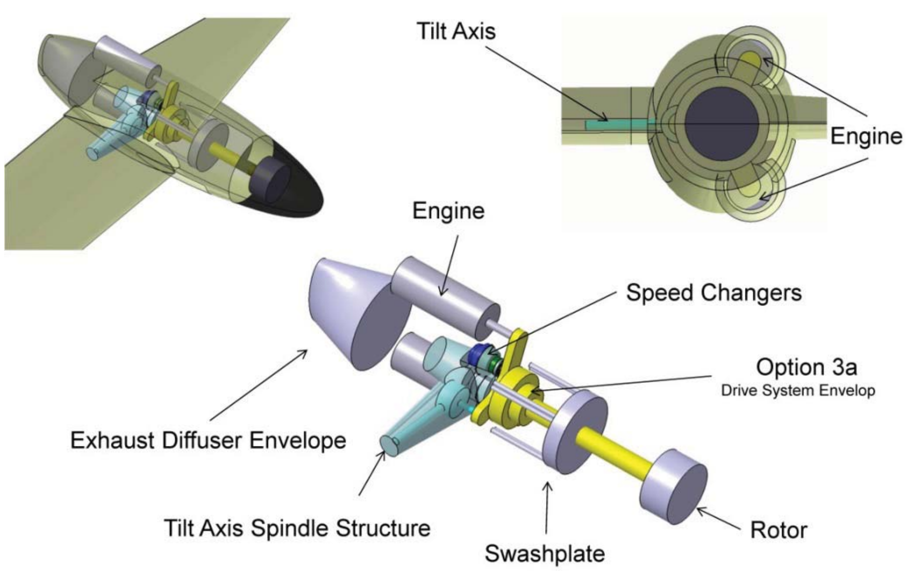

Figure 13.—Option 3a—Engine With Forward Output Shaft and Compound Planetary Transmission.

Figure 14 is the nacelle arrangement for same Option 3a drive system with the aft shafted engine. In this arrangement, the inlet is completely cleared. However, ducting for the outlet is much more complicated as it needs to wrap around the gear train. With the engine shafting pointing aft of the nacelle, the drive system input is now located aft of the tilt axis. With this positioning, the drive system now serves as a balance for the rotor components, thus resulting in a much smaller CG shift and moment for aircraft conversion. It also provides simple structural support for the drive system. However, this location for the drive system also forced a requirement for an extra-long rotor shaft.

Nacelle arrangements with Option 4 drive system are similar to that of Option 3a. Since the two speed changer is in line with the engine, the main gearbox is pushed even further forward with the forward shafted engine (Figure 15). This increase in distance to the tilt axis creates a very large moment and results in a large CG shift as well. Ducting for inlet is more challenging than for Option 3a layouts.

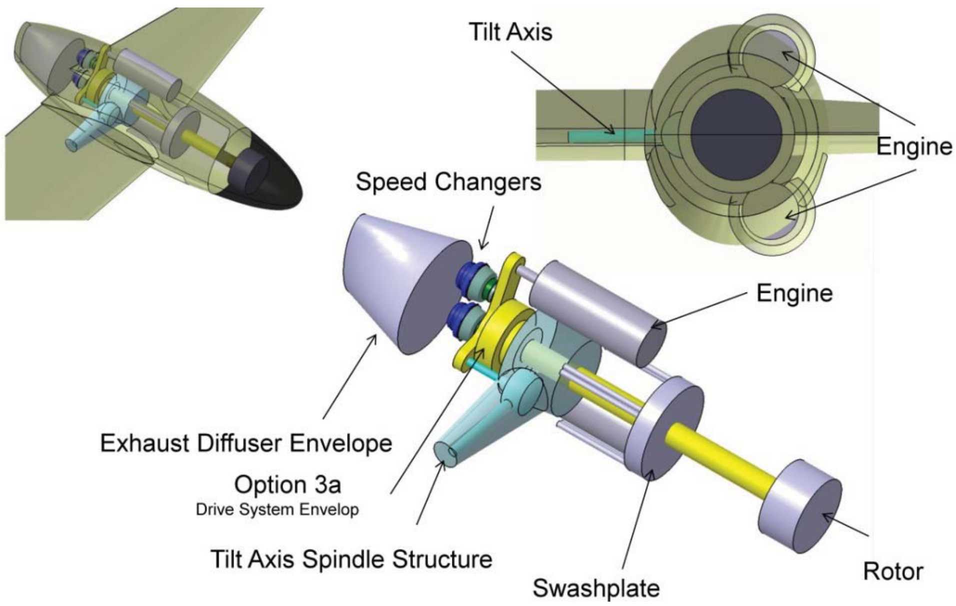

Figure 14.—Option 3a—Engine With Aft Output Shaft and Compound Planetary Transmission.

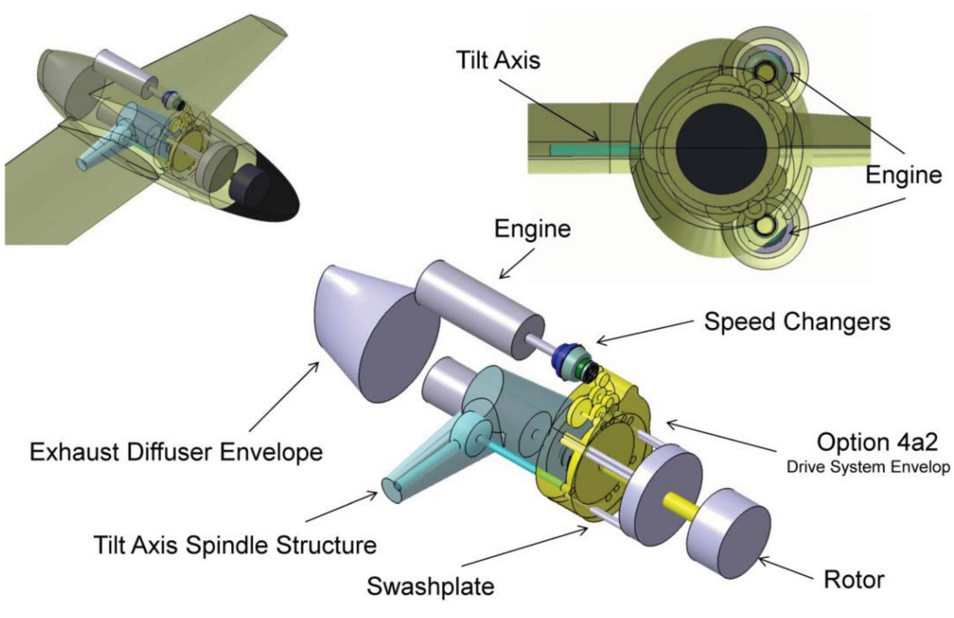

Figure 15.—Option 4—Engine With Forward Output Shaft and Bull Gear Transmission.

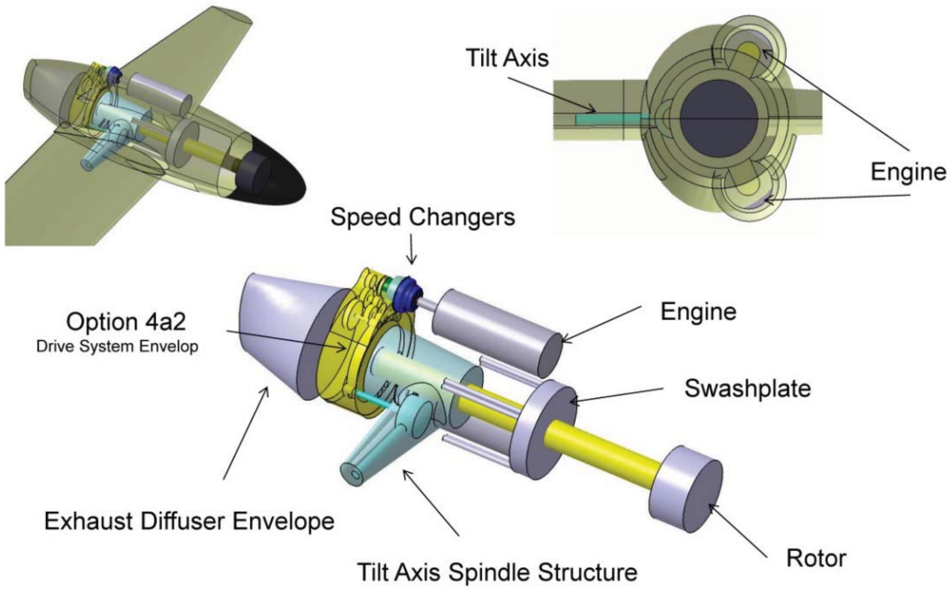

Figure 16.—Option 4—Engine With Aft Output Shaft and Bull Gear Transmission.

However, outlet ducting is much simpler. This layout has the inverse affect paired with the aft shafted engine and as illustrated in Figure 16, the drive system is now further aft, resulting in a much smaller CG shift for the aircraft and smaller moment. The rotor shaft is also much longer however, and outlet ducting for this layout is extremely complicated and undesirable.

3.2 Results

3.2.1 Weight

Component weights in the nacelle were extracted from the aircraft gross weight (as established in previous study projects) for this analysis. Table 4 shows the nacelle weights separated into two major categories, “Fixed” versus “Layout Dependent”. Fixed weight components include controls, rotor components, actuators, IR suppressor, etc. These weights are estimated by scaling from existing aircraft components; i.e., V-22 system weights. The four configurations discussed above each have unique “Layout Dependent” components to satisfy system constraints and the layout geometry. Weight variations for these unique components, such as longer rotor shaft for aft driven engines, unique gearbox configurations (split torque versus compound planetary), and complex structural support requirements, are captured in the “Layout Dependent” portion of the weights analysis.

TABLE 4.—NACELLE COMPONENT WEIGHTS

Preliminary Nacelle Weight Allocation					
		3a Fwd, lb	3a Aft, lb	4 Fwd, lb	4 Aft, lb
Fixed weight	Rotor group	4681	4681	4681	4681
	Nacelle, inlet + exhaust (IRS)	1921	1921	1921	1921
	Engine, upper	787	787	787	787
	Engine, lower	787	787	787	787
	Engine systems	225	225	225	225
	Conversion sys. activation + gearbox	579	579	579	579
	Upper controls	718	718	718	718
	Hydraulic/ electrical/ rotor de-ice / misc.	632	632	632	632
Layout dependent weight	Rotor shaft	540	850	385	1020
	Structural support	650	600	750	700
	Gearbox, main	3725	3725	3825	3825
	Total, weight per nacelle	15245	15505	15290	15875

Weights in Table 4 show that forward shafted engines provide a slightly lighter overall weight than aft shafted engines for both Option 3a and Option 4. This result is partially driven by the constraints of the study. As an example, the hub location and (straight) wing sweep are fixed in this study and affect the rotor shaft length. Aft driven engine configurations require the use of longer rotor shafts to deliver power to the rotor at the front of the nacelle. This long length results in a much heavier rotor shaft weight. For this study, it was assumed that the rotor shaft is comprise of composite (60 percent) and steel (40 percent). Table 5 shows the rotor shaft dimensions and weight for the various options. For Option 3a, the rotor shaft is about 300 lb heavier for the aft driven configuration per nacelle. The weight difference is even more pronounced for Option 4 (aft shaft) at more than 600 lb difference per nacelle as compared to Option 3a (a 4 percent increase in overall aircraft weight). Even though the aft driven engine configurations also result in less structural support weight, the difference in structural weight is only about 50 lb lighter for both options.

TABLE 5.—ROTOR SHAFT DIMENSIONS AND WEIGHT

Rotor shaft sizing			
	Length, in.	Diameter, in.	Weight, lb
3a planetary forward	105	15.5	540
3a planetary aft	150	17	850
4 split torque forward	80	14.5	385
4 split torque aft	180	17	1020

Overall, forward drive engine configurations offer much lighter weights for both Options 3a and 4. The disparity among the results may be decreased with variations in the requirements that affect the rotor shaft length but it is not expected to change the order or outcome of the weight analysis. A consideration not thoroughly evaluated in this study is the effect of rotor shaft integration with the gearbox. Rotor Loads reacted into the gearbox housings and Rotor Shaft diameter effects on the compound planetary system can have significant impacts on weight of those systems, though there are mitigating effects on other structural components. A detailed 3D modeling and sizing exercise would be required to resolve the weight details for these components. System level changes such as wing sweep and tilt axis location should also be considered in that analysis since it is likely that modest changes in these constraints could be beneficial and the most effective mitigation for structural load path, CG shift and weight concerns. An observation outside of the scope of this study and current configuration constraints, it is worthwhile to note that aft shafted engines may be more compatible with fixed engine configurations, where a pylon mounting arrangement, underslung from the wing may benefit with a aft shafted engine.

3.2.2 Vehicle CG

The nacelle components are arranged to minimize the CG shift of the aircraft as it completes its conversion process within the constraints of this study. CG shift is calculated from the nacelle moments imposed at the tilting axis of the nacelle. Table 6 shows that both the best and worst cases of CG shift occurred with Configuration 4. The aft shafted engine configuration provides the best case, and the forward shafted engine is the worse. Looking back at Figure 13 to Figure 16, the reasons for these results are clear. With forward shafted engines, all the heavy weight items, such as drive system and rotor weight are placed in the front of the nacelle, resulting in a huge moment during nacelle conversion. By using an aft shafted engine, the drive system weight is now located behind the tilting axis. This weight becomes a counter balance for the heavy rotor weight instead of being additive.

TABLE 6.—CONFIGURATION MOMENT AT TILT-AXIS

Configuration	Moment at tilt-axis, in.-lb	Aircraft CG shift, in.
3a forward	667k	14
3a aft	554k	12
4 forward	885k	19
4 aft	525k	11

3.3 Assessment

Results illustrated in Table 4 and Table 6 above lead to different conclusions. In terms of weight, forward shafted engines for both Option 3a and 4 are favorable providing the lightest overall nacelle weight. However, to reduce the moment and CG of the aircraft, aft shafted engines provide the minimum shift. The following table (Table 7) contains an overall qualitative assessment of the configurations. Each category provides a decisive factor which are weighted and combined for a total score. Each configuration is then ranked from 1 to 10 (1 being the worst and 10 being the best).

TABLE 7.—CONFIGURATION RANKING

	Weighting factor, %	3a Fwd	3a Aft	4a2 Fwd	4a2 Aft
Weight per nacelle	30	10 15250	7 15500	9 15290	5 15875
Aircraft nacelle conversion moment	30	7 14 in. 667k in.-lb	9 12 in. 554k in.-lb	3 19 in. 885k in.-lb	10 11 in. 525k in.-lb
Structural complexity	15	4 Complex gearbox support	8 Compact	7 Similar to V22	5 Complex interaction with exhaust and speed changer
Inlet/outlet ducting	15	10 No obstruction of inlet/outlet	5 Complex outlet ducting	8 Semi-obstructed inlet ducting	2 Extreme complex outlet ducting
Speed changer location	10	8 Removable speed changer	8 Removable speed changer	5	5
Overall ranking	100	8.00	7.55	6.35	6.05

Configuration Option 3a with a forward shafted engine emerges the most favorable configuration:

- It is the lightest overall nacelle design
- Has a larger (but acceptable) tilt axis moment and CG shift
- Removable speed changer LRU for easy maintenance
- No obstruction for air inlet/outlet flow.
- Simple IR suppressors are located directly behind the engine to reduce heat from engine exhaust.

Configuration 3A with an aft shafted engine came in second as a choice for LCTR2:

- It is 500 lb (less than 2 percent) heavier than the forward configuration
- Offers a better conversion moment and smaller CG Shift than Option 3A with forward shafted engine
- Creates complexity in designing the outlet ducting and IR suppressor.
- Requires the use of a longer rotor shaft to reach the nacelle hub location to drive the rotor.

Configuration 4 with the forward shafted engine came in third:

- It weighs about the same as 3a forward
- Its conversion moment is the largest of the four layouts, resulting in a much larger CG shift
- The location of the two-speed changer also creates an obstructed inlet.

Configuration 4 with the aft shafted engine came in last place:

- Results in the smallest moment and CG shift

- It is the heaviest configuration at 1200 lb heavier than configuration 3A.
- Creates the most complicated exhaust ducting configuration.

4.0 MDAO Tool

4.1 MDAO Tool

The RomaxDESIGNER software tool allows users to model a complete drive train for analysis. It has the capability to build gears, bearings, clutches, etc., to calculate stresses, lives, efficiencies, and much more. Gears are created from gear meshes and positioned on a shaft. Bearings can be modeled as stiffness (concept) bearings to allow for quick analysis of the gear loads without having to specify bearing design in the initial phrase. They can then be replaced by a catalog bearing, from the software library or customized bearing as well. The goal for this portion of the project is to develop a tool and methodology that would allow engineers to conduct trade studies on multiple gearbox designs quickly. The RomaxDESIGNER software package was chosen for this project as a potential tool to accomplish this, since it has the ability to analyze the transmission at an assembly level and much of the desired functionality discussed in Section 2.3 is incorporated in the software.

RomaxDESIGNER models were created for the LCTR2 Drive System from initial sizing information and used as basis for spreadsheet tool development, to create a link between RomaxDESIGNER and Catia as well as from RomaxDESIGNER to parametric weights spreadsheets. The two speed changer gearbox was previously modeled using Catia as part of prior work. This configuration was also re-created in RomaxDESIGNER (see Figure 17). Both models consist of gears, bearings, seals, etc. However, the RomaxDESIGNER model only has rough representations for these components. The Catia model can provide representative component level information for weight tabulation whereas RomaxDESIGNER provides analysis results to size the system in addition to rough weights.

Option 3a with a forward shafted engine was selected to be modeled for this study. The RH gearbox were sized and designed in RomaxDESIGNER (Figure 18). With the RH gearbox assembled and power flow inputs identified, the RomaxDESIGNER program was able to perform duty cycle runs to calculate loads on gears and bearings and output results such as life, power losses, weight, etc. All inputs and dimensions used to create the RomaxDESIGNER model and analysis results can then be exported into XML formats for use in other programs such as an Excel spreadsheet for weights analysis or CAD modeling.

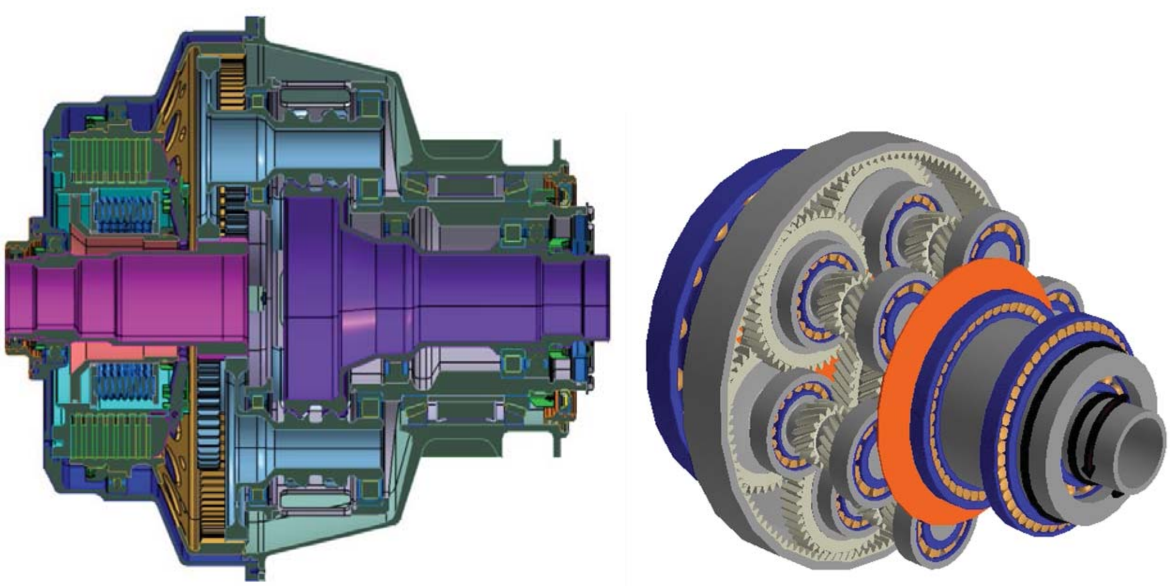

Figure 17.—Two speed changer. Left: As modeled in Catia. Right: As modeled in RomaxDESIGNER.

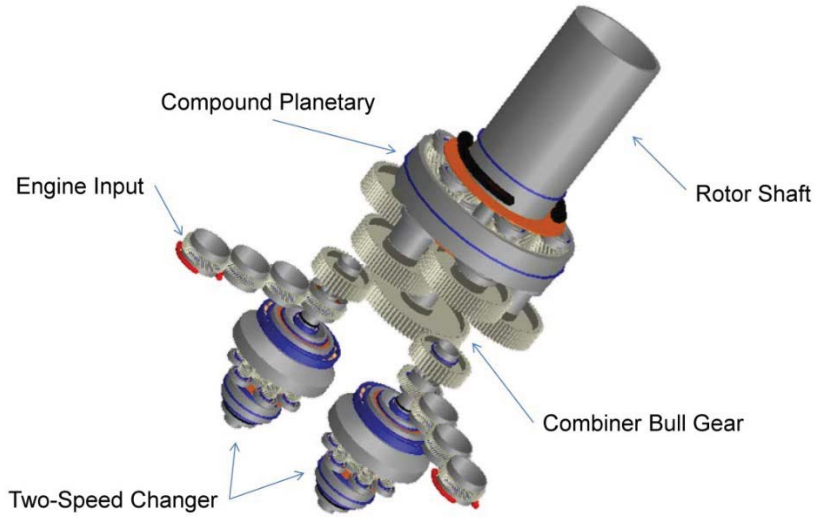

Figure 18.—RH Gearbox as designed in RomaxDESIGNER.

Figure 19 shows a portion of the XML file created for the RH gearbox. The highlighted portions are some of the basic gear geometries needed for the Catia spreadsheet and associated Catia 3D gear models. An Excel macro and dedicated spreadsheet was created to process information from the XML file. The Excel macro, via various code modules, searches through the XML file to extract elements that contains gear geometry information. Once a key word is located, such as ‘Number of Tooth’, it extracts the unique ID associated with that element and all the necessary values to populate the spreadsheet (as shown in Table 8). From the list of extracted gears, the user indicates if the gear is spur, helical, or a ring (internal) gear. The program then populates the information to the corresponding Catia spreadsheet for generating gears in 3D. Since the values from the XML file are in metric units, conversion factors are applied once extracted to Excel. At the current stage, only gear rim and tooth geometry is automated between RomaxDESIGNER and Catia. In a recent version of the software, a RomaxDESIGNER utility function allows gear shaft geometry (not including gear teeth) to be exported from RomaxDESIGNER to CAD systems in VRML and DXF formats. Further automation of this process can be undertaken in future work; however a framework for this process has been established in this project.

Information such as horsepower, speed, and reduction ratios were provided for the parametric weight analysis from XML data, however some limitations with the current technical approach were noted during development. This is partially due to the level of development at which we are applying this process. It appears that RomaxDESIGNER models and the MDAO process are best applied when the concepts and configurations have evolved past initial concepts sketches and into a more detailed preliminary design. The effort required to model each concept suggests that some grooming of possible concepts must occur prior to committing the design to RomaxDESIGNER. Additionally it is noted that RomaxDESIGNER outputs and the legacy parametric weights spreadsheet are not sufficiently developed to be integrated for concept design. The weight spreadsheet requires extensive hands-on experience to determine and apply various qualitative manual inputs to generate aircraft part weights for more complex gear arrangements. Integration of the RomaxDESIGNER models and weights spreadsheets is expected to provide greater benefit later in the design cycle, between concept design and preliminary design, when the scope of changes are reduced and the objectives are focused on optimization of a configuration rather than initial assessment.

For this study, a simplified (more generic) weight parametric spreadsheet (Table 9) was developed to estimate the total weight of each gear mesh. The parametric weight estimate is presented in two aspects. The first includes all the components associated with a rotorcraft transmission; gears, bearings, shafts, seals, housings, etc. The second includes everything in the first except gears and bearings weight. Actual gear and bearing weights can be easily extracted from Catia or RomaxDESIGNER and added to the second aspect for a complete weight overview. This simplified spreadsheet estimates weight by categorizing the mesh types, such as bevel, spur, planetaries, etc. and calculates a weight value depending on gear ratio, hp, and rpm which are linked to the RomaxDESIGNER values. Users need to specify gear mesh type in order for the spreadsheet to use the proper calculation method.


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Figure 19.—Sample RomaxDESIGNER XML Output File

TABLE 8.—RomaxDESIGNER IMPORT SAMPLE EXCEL SPREADSHEET

Go !	Name	UniqueID	Nu	NormalModule	PressureAngle
Spur	Gear 1	4197-3540812564-60954	25	0.009769231	0.34906585
Spur	Bull Gear	4197-3540812507-23309	50	0.009769231	0.34906585
Spur	Gear 2	4197-3540816092-6500	25	0.009769231	0.34906585

TABLE 9.—SIMPLIFIED WEIGHTS SPREADSHEET

							Weight, lb			
Gear box section	b, planets	M, gear ratio	np, no. of pinions	ng, no. of gears	P, hp	Input, rpm	Gear box total	Box less gears and bearings	Quantity	Total
	Input data									
Bevel engine gear box or bevel combiner box		1.758	1	1	4500	6910	198.3	79.3	1.0	79.3
Bevel input set to a larger box or bevel intermediate tail box		1.758	1	1	4500	6910	191.2	66.9	1.0	66.9
Spur section attached to a larger box or spur combiner box		1.758	1	1	4500	6910	183.6	73.4	1.0	73.4
First stage planetary between other stages	4	4.786	1	1	4500	3931	176.2	49.3	1.0	49.3
Second stage planetary or only planetary stage	6	3.650	1	1	4500	821	558.8	195.6	1.0	195.6
Compound planetary	6	12.880			4500	821	2091.0	752.8	1.0	752.8

4.2 Results and Assessment

From the weight breakdown in Table 4, the main gearbox weight estimate per nacelle is approximately 3700 lb. The gear weight can be extracted parametrically and is estimated to be about 1800 lb. RomaxDESIGNER RH gearbox weight for gears is approximately 1870 lb (within 4 percent of parametric weight estimate). As with all other gear analysis programs, RomaxDESIGNER designs the gears using basic gear geometries, such as number of tooth, reduction ratio, diametral pitch, pressure angles, etc. One of the benefits of this program is that it does not only consider a single mesh at a time. Instead, it allows the user to build a complete gearbox with all the necessary meshes and features. Users can review loads, lives, deflections and other considerations that occur during operation. This linkage eliminates some transcription error since the user input for initial input power, rpm, and reduction ratios are used throughout the transmission model. These initial inputs are automatically carried through to the rest of the gear train. Effects from changes made to one element of the transmission modeled in RomaxDESIGNER can be seen through the entire assembly.

Linkages from RomaxDESIGNER to Catia Excel spreadsheet saves the time needed to update these spreadsheets manually and to generate 3D Catia models. With a complex gearbox, the time saving can be quite large, however, construction of RomaxDESIGNER models also becomes a time consuming process. Detailed positioning and iteration of tooth geometry, bearing sizes, shaft configurations, requires considerable effort and are generally not completed during a concept formation phase, and thus not entirely within the scope of this study for the propulsion pod concepts. In general, this task is a necessary step and it appears to be handled well in RomaxDESIGNER when compared to previous processes using a variety of tools and modeling environments. The appropriate usage of RomaxDESIGNER appears to be after initial concepts are formed, to optimize the gearbox arrangements as a part of a preliminary design effort.

RomaxDESIGNER's allowance of using stiffness bearing for initial calculation is beneficial. It allows the user to focus on sizing and positioning the gears first. It also provides a fairly easy way to convert the stiffness bearing model to an actual catalogue bearing within RomaxDESIGNER when bearing lives are needed. However, the bearing selections from the RomaxDESIGNER library are currently limiting. RomaxDESIGNER needs to include more bearings from common bearing catalogs. Although it is also very easy to customize a bearing, it would be simpler for the user to grab bearings from catalog information.

Boeing's proprietary parametric weights spreadsheet requires a lot of manual inputs from the user by integrating past experiences, which cannot be captured in software. However, a simplified, generic spreadsheet was developed to provide a link with RomaxDESIGNER. The only values from the RomaxDESIGNER files that can be used in the simplified weights spreadsheet are power, engine input rpm, Rotor output rpm, and reduction ratios. This spreadsheet then provides output parametric weight values. One caveat for this simplified process is creating the automation process for compound planetary systems. Compound planetary systems vary from one setup to another, making it complicated to create one set of equations to automatically calculate the weight; therefore making the automation process difficult. To make this work, each compound planetary system would need to be customized. This is an area for further development in the future.

It is fairly simple to extract the necessary information from the RomaxDESIGNER XML files. The linkage spreadsheets are set up so that it will be able to extract the indicated values for any configuration in RomaxDESIGNER as long as the XML naming conventions remain the same. To use it with a different RomaxDESIGNER configuration, the user would just need to change the import file to the desire one. However, the linkage spreadsheets do require a few manual inputs from the user. They need to specify gear type in order for the spreadsheets to generate gear blank geometry. The weights spreadsheet also requires user to indicate the type of gear mesh to calculate parametric weight. Another potential issue is the language of the RomaxDESIGNER XML files. If RomaxDESIGNER decides to change the naming convention of their XML map, the macros for both gear geometry and weights spreadsheets would need to be updated as well to maintain the link.

5.0 Conclusion

Not all of the goals were accomplished as originally set out for this project but significant progress was made toward the overall project goals, both for configuring the LCTR2 drive train within the vehicle configuration constraints and also for development of an MDAO tool for drive train design and analysis. Two different drive system configurations were developed (conceptually) and both paired with forward and aft shafted engines to provide four possible nacelle layouts for the LCTR2 vehicle. Nacelle layouts also considered the placement of engine inlets, rotor components and controls, structural elements, and exhaust provisions. A semi-automated link was also created between RomaxDESIGNER, Catia gear profile generating spreadsheet, and the weights spreadsheet.

Overall, forward shafted engine seems to work well for the LCTR2 vehicle. The placement of the components and the space favored a compound planetary system (Option 3a) with front shafted engine. It provides the lightest weight option for the vehicle even though it generates a bit more CG shift during nacelle conversion than some of the other configurations. It provides clear path for inlet/exhaust and provides a maintainable location for the speed changer in comparison to others. Even though aft shafted engines provided better control of CG shift during conversion, it tends to be heavier due to the weight of a long rotorshaft.

The development of an MDAO tool and methodology was a partial success. The primary goal for the MDAO tool was to create a seamless procedure to rapidly iterate among various configuration designs. Outputs from RomaxDESIGNER were easily imported to spreadsheets. Boeing successfully integrated RomaxDESIGNER outputs to a Catia input file to generate gear geometries, but had partial success for a comprehensive link between RomaxDESIGNER and the parametric weight spreadsheets. A simplified weight spreadsheet was developed to generate the link with RomaxDESIGNER. This simplified version allow user to calculate gearbox weight with readily available information such as power, speed, and reduction ratio. However, it still needs improvements in certain areas, such as weights for compound planetary systems.

For the goal of creating CAD models from the RomaxDESIGNER analysis, spreadsheets and macro programs were constructed so that gear geometry and analysis results were extracted in XML format, and were easily imported to Excel spreadsheets. Gear shaft parameters were then used with Boeing's gear geometry spreadsheet to create the 3D solid models. Updates to the RomaxDESIGNER models would also be automatically updated in the spreadsheets, thus updating the Catia 3D model. This eliminates human error as well as saves time to update the spreadsheets manually.

6.0 Future Work

6.1 Nacelle Configurations

Though the scope and constraints in this project did not permit a broader study of vehicle configurations and nacelle arrangements, some observations can be made for future work. System level changes such as wing sweep and tilt axis location should be considered in future configuration studies since it is likely that modest changes in these constraints could be beneficial as a mitigation strategy for structural load path, CG shift, and weight concerns. Forward wing sweep will result in (forward) relocation of the nacelle pivot axis which will effectively shorten the rotor shaft length and provide a better weight distribution of nacelle components around the pivot axis. In addition, it may be possible to transmit rotor loads directly from the rotor shaft to the pivot structure, eliminating gearbox housings from that loadpath. Tilting engines and nacelles were the baseline configuration for this study, and operational risks from hot exhaust gas impingement on landing surfaces, exhaust re-ingestion, and debris ingestion are known and noted in this study and previous work. If the scope of future work widens to include fixed engine configurations, it is worthwhile to note that aft shafted engines may be more compatible with these vehicle configurations. As an example, a pylon mounting arrangement, underslung from the wing may benefit from an aft shafted engine. This would not be an insignificant effort however, since fixed engine configurations for tiltrotors have their own unique challenges, including weight and CG shift during nacelle transition.

6.2 RomaxDESIGNER Tool Improvement

One of the goals of the MDAO tool was to assist in the creation of 3D models in Catia for weight analysis as well as to optimize the placements of components. It would be beneficial if RomaxDESIGNER models could be easily imported directly into 3D modeling tools such as Catia and vice versa, back into RomaxDESIGNER. Currently, Boeing users need to construct gear analysis and models in RomaxDESIGNER and then repeat a portion of the work to build a very similar model again in Catia for accurate weight values as well as component detail design and assembly models. Boeing communicated with Romax Technology IT to develop a seamless conversion from RomaxDESIGNER to a usable model in CAD as well as an improved method for analyzing conceptual gears. Since this discussion and during the execution of this project, Romax Technology provided an updated version of their software, Version 14.5. This version offers an updated version of their “Concept” tool (see Figure 20). While RomaxDESIGNER Version 14.0 had a “Concept Modeler” tool as well, it was only used to create concept gear meshes with no analysis tool at that stage. The new version provides quick initial analysis of the gear mesh by providing recommended sizes based on initial power input. It also allows the user to view the models in 3D. From this tool, designers can also export RomaxDESIGNER designs into STEP files and bring it into any CAD software (see Figure 21). However, models are not generally modifiable in CAD.

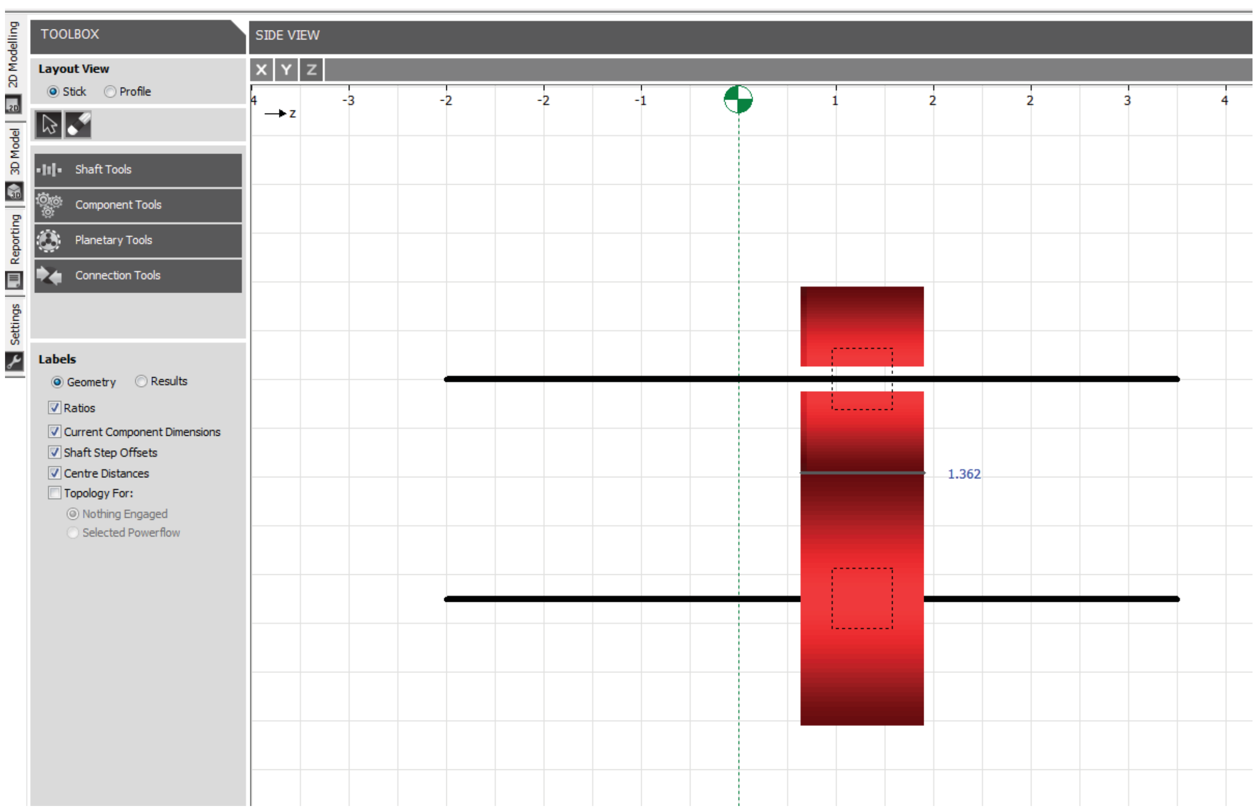

Figure 20.—RomaxDESIGNER Concept Software (2D View)

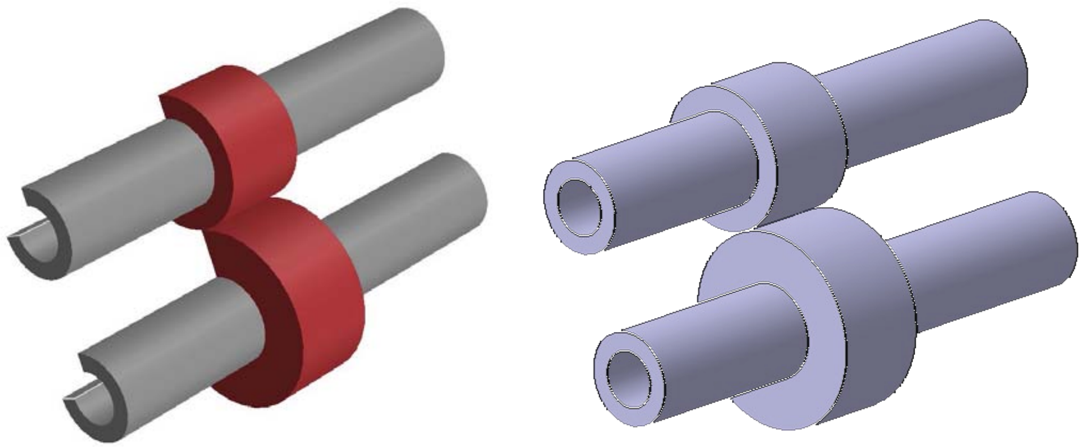

Figure 21.—RomaxDESIGNER Concept Software (3D View). Left: 3D view in RomaxDESIGNER. Right: Step File from RomaxDESIGNER.

Further improvements are needed to streamline this software. The analysis portion of the RomaxDESIGNER Concept software provides recommended face width and center distances. It would be desirable to have results in terms of stresses. Stress results are only available in the detailed design tool bar within Romax, which requires more time to develop. Boeing will continue the discussion with Romax Technology IT to find improvements. Unrestricted movement of models between CAD systems and RomaxDESIGNER with editable features is desirable, and will benefit system level analysis and optimization of the designs. Greater functionality in this area for model transfer to CAD systems will be helpful for future work. A ‘seamless’ transfer method is still an important goal, but perhaps a larger view would include direct data transfer to manufacturing engineers in a universal format for manufacturing planning and machine programming.

6.3 Weights Spreadsheet Improvement

One of Boeing’s initial goals for this project was to automate the parametric weights calculation. Experimentation in this project indicated that both RomaxDESIGNER and the parametric spreadsheet require improvement and greater integration. It is important to use the parametric weight analysis procedures that are tuned to Boeing history and products since RomaxDESIGNER cannot provide that information. Additional information can be provided by the RomaxDESIGNER tool to allow for a better integration, which will be pursued in future work. The spreadsheet analysis procedure can also be updated, the compound planetary system, for example, requires further development in order to automate the calculation process. The variations in compound planetary system arrangements differ greatly which makes a huge difference in weight calculations. Currently these calculations occur outside of the automatic process and rely on knowledge about the relative diameters of all gears involved. To perfect the automated linkage between RomaxDESIGNER and Excel, Boeing needs to identify compound planetary configurations of interest and create unique equations to calculate the weight and to refine the weight algorithms and user dialogue to include modifiers and factors based on Boeing experience and weight trend history.

Appendix A.—Statement of Work

Additional detail is provided below for the WBS elements of this study project as refined during execution.

A.1 WBS 1.0—Develop Conceptual Propulsion Pod Layouts

WBS 1.1 Boeing shall define the key drive system requirements and features based on the NASA LCTR2 vehicle and mission concept

WBS 1.1.1 LCTR2 Vehicle and propulsion system requirements will be derived from NASA studies reported in references 1 and 2 and documented with an informal report

WBS 1.1.2 Performance parameters, engine and drive system requirements may also be taken from work performed in previous NASA studies reported in references 3 and 4 with NASA concurrence

WBS 1.1.3 Requirements, data and configurations drawn from prior work or established in this project with NASA guidance will be documented with an informal report that will be included or integrated in the final project report

WBS 1.2 Boeing shall develop conceptual engine / drive layouts using front and aft-drive turbine engines.

WBS 1.2.1 Schematics and operating parameters will be developed for propulsion pod / drive train configurations of interest

WBS 1.2.2 With NASA's concurrence, Boeing shall determine key parameters for front- and aft-drive turbine engines, including at least weight and dimensions. This data will be partially derived from engine models defined in previous work described in references 3 and 4. Boeing shall address associated requirements for engine protection from particle ingestion, icing and engine exhaust diffusers, which are directly driven by the installation. Additional engine data and modeling will be defined with the assistance of engine manufacturer Rolls Royce Liberty Works. Engine stability margins will not be quantitatively analyzed due to the depth and complexity of this analysis but may be comparatively addressed in discussion and reporting.

WBS 1.2.3 Boeing's engine / drive layouts shall include capability for 50 percent rotor speed reduction achieved through engine-alone or employing multispeed transmissions between the engine and the rotor speed-reduction gearbox. In the latter arrangement, Boeing shall include a multispeed transmission for each engine and cross shafting. This data may be derived from engine and drive system models defined in previous work described in references 3 and 4.

WBS 1.2.4 In the development of the propulsion pod layouts Boeing shall include overall and component-level models, sketches and information at a level of detail sufficient to delineate key parameters (weight, overall component dimensions, cooling and other requirements, e.g. access for inspection, maintenance and repair) for various major engine and drive components to the extent possible in this statement of work. Components and assemblies will be arranged with respect to notional vehicle coordinate systems, though modeling of LCTR2 structure and interfaces is not anticipated within the scope of this project. Where possible Boeing will define location on the LCTR2 vehicle and potential interactions among systems. Weight of engine system and variations will be defined by Rolls Royce Liberty Works. Weights for the remainder of components will be defined by Boeing primarily through parametric analysis and also through analysis of CAD models.

WBS 1.2.5 Boeing's engine / drive layouts shall optimize overall system mass, efficiency, performance, operability, maintainability; with the relative weighting among these overall system parameters to be determined by Boeing with NASA concurrence.

WBS 1.2.6 During development of conceptual layouts, the depth of analysis to determine component characteristics to optimize overall system characteristics may require Boeing shifting resources and depths of analysis among the various components, with NASA concurrence.

WBS 1.3 Boeing shall define the key technical challenges for each layout developed, identifying those items that are common to various layout concepts as well as those unique to a particular layout or engine type.

WBS 1.3.1 Identify Technology challenges and gaps associated with the integration of rotor drive and engine of the LCTR2 vehicle concept

WBS 1.3.2 Identify the unique challenges associated with front- and aft-drive turbine engine installations.

WBS 1.4 Project management and Reporting Tasks.

WBS 1.4.1 Kick-off meeting to be held as Web meeting within 30 days ARO to discuss goals, objectives, methodology and desired end results

WBS 1.4.2 Project management will include periodic bi-weekly telephone/Web meetings with NASA technical monitors, budgetary management,

WBS 1.4.3 Final Report Final report shall be formatted for NASA Contractor Report (CR) detailing all work performed, analyses, conceptual layouts, sketches and descriptions, knowledge gaps and technology challenges and gaps. A draft report will be submitted by month 8 of the task order POP. Analyses and models developed under this task order shall be delivered in a format acceptable to NASA. In the case of simple equations, it is sufficient to include these equations in the final report. Other models (i.e., Excel spreadsheets or Matlab models) shall be supplied to the government with unlimited rights. The logic and methodology used to guide this work shall also be reported in the final written report such that Boeing's insight and understanding behind their work is imparted to NASA. Pursuant to Contract Clause H.24, Special Data Rights, all deliverables provided under this Task Order NNC11TA80T in the Final Report will be submitted to the Government with "Unlimited Rights" as the term is defined in contract section I. 52.227-14 Rights in Data General.

WBS 1.4.4 Final Oral Briefing/ presentation to be held at NASA Glenn Research Center (GRC) using a Web-based electronic meeting media with other relevant participants.

WBS 1.4.5 Boeing will use established Risk Management practices and will notify NASA Glenn Research Center (GRC) of any significant risks to the performance of this task order, such as potential loss of key personnel or concerns that have the potential to affect schedule milestones and/or goals.

A.2 WBS 2.0—Optional Task for Analysis and Optimization of Drive System.

WBS 2.1 Define Air Vehicle /Drive Train MDAO Approach.

WBS 2.1.1 Define commercial software packages, weight algorithms and data requirements for desired end state of analysis procedure. Candidate tools include ROMAX, Model Center, and Excel spreadsheets, etc.

WBS 2.1.2 Flowchart data transfer and analysis requirements.

WBS 2.2 Construct MDAO Demonstration Tool

WBS 2.2.1 Define weight analysis procedure from existing weight trend relationships and algorithms and set up generalized spreadsheet with weight algorithms.

WBS 2.2.2 Define Initial Inputs and limits for gear/bearing analysis and /or standardized configuration descriptions and/or generalized GUI menus and /or interface with parametric CAD (Catia) geometry models.

WBS 2.2.3 Define Sensitivity studies and iterative analyses that can be performed during drive system analysis.

WBS 2.2.4 Combine Tools, construct links, test functionality for overall vehicle sizing capability with Model Center approach

WBS 2.3 Conduct MDAO Air Vehicle / Drive Train Sizing Exercise - Training and Demonstration

WBS 2.3.1 Conduct Training and familiarization for ROMAX, Model Center or other component tools as needed

WBS 2.3.2 Using data from WBS section 1.0 of this project, conduct sizing exercise for LCTR2 drivetrain/ vehicle.

WBS 2.4 Option Task Reporting and Documentation

WBS 2.4.1 Additional Kick-off meeting to be held as Web meeting within 30 days ARO for WBS 2.0 optional tasks to discuss goals, objectives, methodology and desired end results for this effort

WBS 2.4.2 Provide Addendum report to project final report. Description in final report will describe methodology and analysis results using tools developed in WBS section 2.0 for at least one version of the LCTR2 propulsion drivetrain as defined in WBS section 1.0. Report will also include an assessment of the effectiveness for the tools and methodology developed in this project.

References

1. Robuck, Mark, Wilkerson, Joseph, Maciolek, Robert, Snyder, Christopher A., Zhang, Yiyi, "Study and Sub-System Optimization of Propulsion and Drive Systems for the Large Civil TiltRotor (LCTR2) Rotorcraft," American Helicopter Society 69th Annual Forum, Phoenix, AZ, May 21-23, 2013.
2. Robuck, Mark, Wilkerson, Joseph, and Snyder, Christopher A., Vonderwell, Daniel, "Design Study of Propulsion and Drive Systems for the Large Civil TiltRotor (LCTR2) Rotorcraft," American Helicopter Society 67th Annual Forum, Virginia Beach, VA, May 3-5, 2011.
3. Snyder, Christopher A., Robuck, Mark, Wilkerson, Joseph, and Nordstrom, Carl, "Summary of the Large Civil TiltRotor (LCTR2) Engine Gearbox Study," American Helicopter Society International Power Lift Conference, Philadelphia, PA, October 2010.
4. Robuck, Mark J, Wilkerson, Joseph, Maciolek, Robert, Vonderwell, Dan, "The Effect of Rotor Cruise Tip Speed, Engine Technology and Engine/Drive System RPM on the NASA Large Civil Tiltrotor (LCTR2) Size and Performance," March 2012.
5. Ford, A., Bloxham, M., Turner, E. Clemens, E., and Gegg, S., "RTAPS VSPT Contract NNC10BA14B, Design Optimization of Incidence-Tolerant Blading Relevant to Large Civil Tilt-Rotor Power Turbine Applications," NASA/CR—2012-217016, December 2012.
6. Schmidt, Arling H., "A Method for Estimating the Weight of Aircraft Transmissions," Society of Allied Weight Engineers, Inc., Philadelphia, PA, May 24-26, 1976.
7. Dyess, Stephen B., "Drive System Weight Optimization," Society of Allied Weight Engineers, Inc., San Diego, CA, May 20-22, 1991.
8. Gmirya, Yuriy, Alulis, Matthew, Palcic, Peter, Leslie, Leigh, "Design and Development of a Modern Transmission: Baseline Configuration of the CH-53K Drive System," American Helicopter Society 67th Annual Forum, Virginia Beach, VA, May 3-5, 2011.