NASA/TM-20220009567

RVLT Concept Vehicle Powertrain Arrangement Study and Candidate Powertrain System Test Arrangements

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August 2022

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This work was sponsored by the Advanced Air Vehicle Program
at the NASA Glenn Research Center

Level of Review: This material has been technically reviewed by technical management.

This report is available in electronic form at http://www.sti.nasa.gov/ and http://ntrs.nasa.gov/

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Abstract

This work was motivated by the vision of the NASA's Revolutionary Vertical Lift Technology (RVLT) Project and project goals to support the Urban Air Mobility mission. A RVLT concept vehicle, namely the side-by-side helicopter with hybrid electric propulsion, was selected to conduct a powertrain study. The specific objectives of this work were to explore powertrain designs for the RVLT side-by-side hybrid electric (SbS-HE) concept vehicle to assess powertrain configurations, and in the process identify general trends for design tradeoffs, technology barriers, and research needs. A notional powertrain for the vehicle was created, and this led to identifying some mechanical components for development and testing. Three powertrain component concepts designs were created, namely a pericyclic drive mast gearbox, a control clutch, and an overrunning cutch. The design approach and evolution are documented. A universal combining gearbox was conceived and designed that would extend the capability of a NASA test facility for testing and demonstration of technologies for urban air mobility vehicle powertrains. Candidate powertrain test arrangements as enabled by the proposed universal combining gearbox are explained and depicted.

Acronyms

CAD	Computer Aided Design
eVTOL	Electric Vertical Take Off and Lift
FHA	Functional Hazards Analysis
FMECA	Failure Modes and Effects Criticality Analysis
GRC	Glenn Research Center
GTE	Gas Turbine Engine
M-G	Motor Generator
MGU	Motor Generator Unit
OEI	One Engine Inoperative
PSU	Penn State University
RVLT	Revolutionary Vertical Lift Technologies
SbS	Side-by-Side
SbS-HE	Side-by-Side Hybrid Electric
UAM	Urban Air Mobility
VTOL	Vertical Take Off and Lift

Introduction

The work effort described within was motivated by the research goals and focus of NASA's Revolutionary Vertical Lift Technologies (RVLT) Project. The vision of the project is to create a future where vertical take-off and lift (VTOL) configurations operate quietly, safely, efficiently, affordably, and routinely as an integral part of everyday life. Toward that vision, the project research seeks to develop and validate tools, technologies, and concepts to overcome key barriers. A special focus of the RVLT project is the Urban Air Mobility (UAM) concept, a subset of the Advanced Air Mobility mission that is projected to have the biggest economical impact and has the most difficult technological challenges (Ref. 1).

Quoting Johnson and Silva (Ref. 1), "The NASA Revolutionary Vertical Lift Technology (RVLT) Project is developing UAM VTOL aircraft designs that can be used to focus and guide research activities in support of aircraft development for emerging aviation markets. These NASA concept vehicles encompass relevant UAM features and technologies, including propulsion architectures (distributed electric, hybrid, turboshaft, and diesel), highly efficient yet quiet rotors and aircraft aerodynamic performance and interactions. The configurations adopted are generic, intentionally different in appearance and design detail from prominent industry arrangements, while capturing many of the essential technology features. The purpose of the NASA concept vehicles is to provide specific configurations for communication of NASA's Urban Air Mobility research, for support of design and analysis tool development, for technology trade studies and sizing excursions, and for modeling operational scenarios."

The work within is based on one of the four NASA RVLT concept vehicles, the side-by-side helicopter with hybrid electric propulsion, (SbS-HE) (Refs. 2 and 3). Herein the word powertrain is used to mean the rotating components providing propulsion power to the rotors. Also influencing this work was a NASA funded study with primary objectives to identify failure modes and hazards associated with some concept vehicles and to perform functional hazard analyses (FHA) and failure modes and effects criticality analyses (FMECA) for each. Such work was ongoing during initiation of this work, and results of that study have since been reported (Ref. 4).

The specific objectives of this work were to explore powertrain design for the RVLT side-by-side hybrid electric concept vehicle to assess powertrain configurations, and in the process identify general trends for design tradeoffs, technology barriers, and identify research needs that could be designed, built, and tested as components and in a scaled powertrain system at NASA GRC.

This report is comprised of three numbered sections and a summary.

- **Section 1, "Study and Concept Development Execution**" covers the overall study and concept development effort and overviews two components identified for the RVLT Side-by-Side Hybrid Electric (SbS-HE) Concept Vehicle, both of these components being candidates for development, design, and test at NASA GRC in a scaled powertrain system test.
- **Section 2, "Developing a Conceptual Propulsion Powertrain System for the RVLT Side-By-Side Concept Vehicle"** overviews the development of a possible propulsion powertrain for the SbS-HE vehicle and related powertrain components that may also be possible candidates for other vehicles.
- **Section 3, "Candidate Facility and System Test Configuration for SbS-He Powertrain and Others"** overviews possible developmental and demonstrations testing of VTOL powertrain technologies possible in the NASA Glenn Research Center's Variable Speed Drive Facility.

Section 1.—Study and Concept Development Execution

Execution of the work objectives relied mainly on the publicly available NASA technical papers and presentations, directions from RVLT Project Management, and input from the periodic status updates for the hazards and failure modes contracted study performed by the Boeing Company (Ref. 4).

The Side-by-Side Hybrid Electric (SbS-HE) concept vehicle was the focus vehicle of this study (see Figure 1 and Figure 2, coming from RVLT project documents). Caution that Figure 1 is a schematic only and does not convey exact details of the powertrain concepts. For example, the schematic shows three clutches, each depicted by the same simple icon, but the functionality of the clutch at the motor generator differs from the others, as will be apparent after further discussion. This design exploration effort focused on the electromechanical powertrain system and required components and provisions necessary to integrate the electrical propulsion and power generation components into an overall hybrid electromechanical propulsion powertrain system.

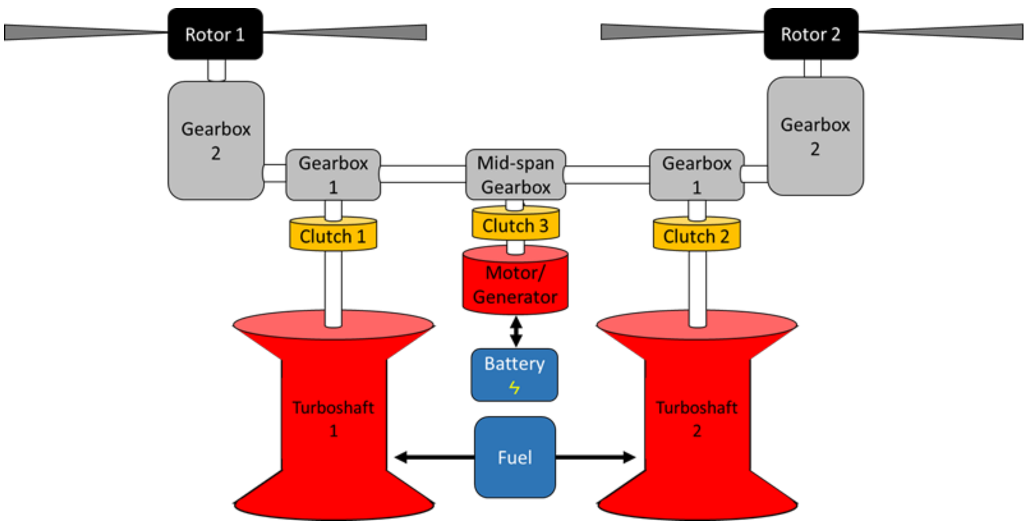

Figure 1.—Side-by-side hybrid electric vehicle powertrain schematic.

Figure 2.—NASA RVLT SbS concept vehicle.

Methodology and Scope

This work effort began with reviewing the available documentation and collecting other relevant data to:

- Establish a set of basic design requirements for the hybrid-electric powertrain system for the RVLT SbS-HE concept vehicle.
- Investigate conventional rotorcraft vehicles with similar propulsion powertrain configurations to establish parallels that could form a basis to develop a preliminary concept.
- Identify barriers, both at the component level and application at the system level.
- Identify components and/or a full/partial system that require investigation in the form of design and test.

The first step of the conceptual design study began with creating a basic overall powertrain system. Second, the study delved deeper into individual components making up the overall system concept. Third, the matured component descriptions were incorporated back into the overall system in an iterative manner.

This report summarizes concept development for the following system and components:

- RVLT SbS-HE Concept Vehicle Propulsion Powertrain
- Primary 2-Stage Reduction Gearbox at the twin Gas Turbine Engines
- Right Angle Drive Gearbox (Engine Input to Rotor and Cross Shaft Double Output)
- Pericyclic Rotor Mast Gearbox Concept (Low Mass High Reduction Ratio Drive)
- Control Clutch (at Motor-Generator), Bi-Directional Power Flow (Propulsion/Charging)
- Overrunning Sprag Clutch (near Gas Turbine Engines)
- Combining Gearbox (Cross Shaft Pass Through and Motor-Generator Input and Output)

From the above, the study identified technology gaps and powertrain subsystems and/or components that could be developed and tested to enable integration into a hybrid electric-mechanical powertrain system.

Powertrain Technology Gaps and Components for Potential Development and Test

The following components were identified from the above work as not existing and therefore as needing development and test:

- Control Clutch (at Motor-Generator); does not include a positive mechanical lock.
- Overrunning Sprag Clutch (at Engines); possible integral feature to attenuate the magnitude of engagement torque spikes associated with overrunning clutches.
- Universal Combining Gearbox (enabling facility component testing of SbS-HE powertrain as well as other configurations, as will be shown later below).

Control Clutch at Motor-Generator (M-G)

The motor-generator control clutch connects the combining gearbox, centrally located in the cross-shaft system, to the motor-generator. The above is identified as clutch number three in NASA RVLT SbS-HE powertrain schematic in Figure 1. Power flow at this clutch is bi-directional depending upon the motor-generator operating mode. In addition, the motor is disconnected from the powertrain during gas turbine engine (GTE) starting. A sprag clutch cannot provide the required functionality. Thus, either the motor-generator is rigidly connected, always spinning (not a favored selection in this study due to motor bearing reliability), or it is a control (on-off) clutch. System studies should identify whether clutch control should be electric or hydraulic and define clutch operations to best guide system and component developments. With clear direction of the method of control not available, a proposed concept developed as part of this work effort and described below easily enables exploration of both methods of control.

The NASA/CR—2019-220217 (Ref. 4) provides details regarding operation of the Motor-Generator Unit (MGU) and clutch that supports the above operational scheme:

> "*A friction disc clutch is located between the output of the MGU and the spiral bevel gear mesh. The friction disc clutch is used to couple or decouple the MGU from the primary powertrain. Detailed mission planning and usage spectrum information is required to determine the schedule for clutch engagement and disengagement, but it is likely that the clutch would be disengaged (decoupling the MGU from the powertrain) during start up and in emergency conditions and engaged (coupling the MGU and powertrain) during flight while the MGU powers the rotors or while the MGU is being charged by the turboshaft engines*."

From the above, the motor-generator is to be disengaged during engine startup and engaged once the gas turbines are running at idle speed. Motor-generator coupling to the propulsion powertrain will occur at, or above, engine idle speed, requiring clutch engagement at, or above, 10,000 rpm.

A new concept was required for a controlled-clutch at the motor-generator, where power flow changes between hover and cruise flight modes (i.e., power assist during hover and generator mode during cruise). The concept, unlike the clutch designed for the NASA Two-Speed Drive (Ref. 5), employs speed sensors to enable synchronizing the motor-generator speed to the speed of the combiner gearbox, smoothly engaging the clutch, then smoothly powering up the motor to provide the required additional share of the overall power for hover mode. The vehicle hover mode requires both Turboshaft Gas Turbines and the Motor-Generator in motor mode to provide power to the rotors.

The concept control clutch with integral synchronous speed control and the accompanying electronic motor-generator control system to switch between motor and generator operating mode will be needed to provide smooth engagement and disengagement with no torque spike caused by the M-G control clutch.

- The control clutch concept configuration is identified as a UAM powertrain specific component for development and operational test. This component is required for a hybrid-electric configuration requiring both electronic clutch control and motor-generator conversion (switching) control.

Overrunning Sprag Clutch at Gas Turbine Engine

Within this study, a new conceptual overrunning sprag clutch was created for use "near" the engines. The above is identified as clutch number 1 and number 2 in the initial NASA RVLT SbS-HE powertrain in Figure 1. In lieu of a clutch being integral with the gearbox, a modular component approach was created to enable the flexibility to easily position the clutch at other locations within a given propulsion system. The study resulted in placing the overrunning clutch at a location different from the depiction of the RVLT SbS-HE powertrain of Figure 1. The overrunning clutch instead was located in this study after the output of a gear reduction stage following the GTE. Located in this manner, when the clutch operates in overrunning mode the output shaft of the gear stage and associated gearing and bearings connected to the clutch will stop rotating, thereby creating less drag for the remaining operating engine. The clutch concept configuration utilizes two overrunning sprag clutches in parallel, as is common practice in rotorcraft. The basic design in this study employs a commercial automotive overrunning sprag clutch with an appropriate torque capacity for the SbS vehicle, previously used in the NASA Two-Speed Drive design (Ref. 5).

The basic concept clutch was adapted to include integral torsion compliance to reduce the magnitude of potential engagement torque spikes caused by the metal-on-metal engagement of an overrunning sprag clutch. Torsional vibration is known to cause an intermittent disengagement at the sprag clutch and slippage leading to torque spikes as well as wear of sprag elements and races. This can be a problem with small twin-rotor twin-engine vehicles. The above torsional compliant concept may also be relevant to the RVLT Tiltwing concept vehicle. Details on integral torsion compliance/damping are discussed later in sections highlighting individual component development in Section 2.

- The overrunning sprag clutch is required for hybrid-electric configuration with cross shafting. The concept overrunning clutch, with or without integral torsion damping, is identified for development and test. The torsional compliance concept extension could be developed and tested as a component in parallel with current RVLT UAM motor focus.

Universal Combining Gearbox

While not a component for UAM vehicle powertrains, this facility component was identified as needed to enable the ability to test a variety of UAM powertrain configuration models, in some cases by combinations of physical and emulated components. The lacking facility component is a combining gearbox that would be versatile for experiments involving cross shafting, power combining, or power splitting. A concept was created for a universal combining gearbox with a highly adaptable configuration, easily reconfigurable, to adapt to a variety of power train configurations.

- The Universal Combining Gearbox concept is identified as an enabling facility component(s) that will increase the facility capability to test component and system level powertrains that have multiple power sources such as gas turbine engines and supplemental electric motors and the control of motor-generator in a physical system. The above gearbox can combine the current facility configuration of separate a motor test bed and transmission test rig into an integrated powertrain facility, as well as the ability to operate as separate test rigs.

Section 2.—Developing a Conceptual Propulsion Powertrain System for the RVLT Side-By-Side Concept Vehicle

The next work of this project began with reviewing the available RVLT Side-by-Side (SbS) concept vehicle documents and other twin rotor vehicles documents, such as for the CH-47 Chinook Helicopter powertrain configuration, for potential relevance to the effort. Also, the Army Helicopter Design Guide, (Ref. 6) was reviewed to obtain additional general guidance.

In the above SbS-HE concept vehicle, multiple right-angle drive gearboxes are required (input from the engine, vertical output to the rotor, and input/output, connecting the engine horizontally to the cross-shaft on the opposite strut). In between the above, the mid-span (combining) gearbox, providing a right-angle connection to a clutch and the motor-generator. This requires developing all of the above, and others not identified, beyond the level of detail in the SbS-HE figures.

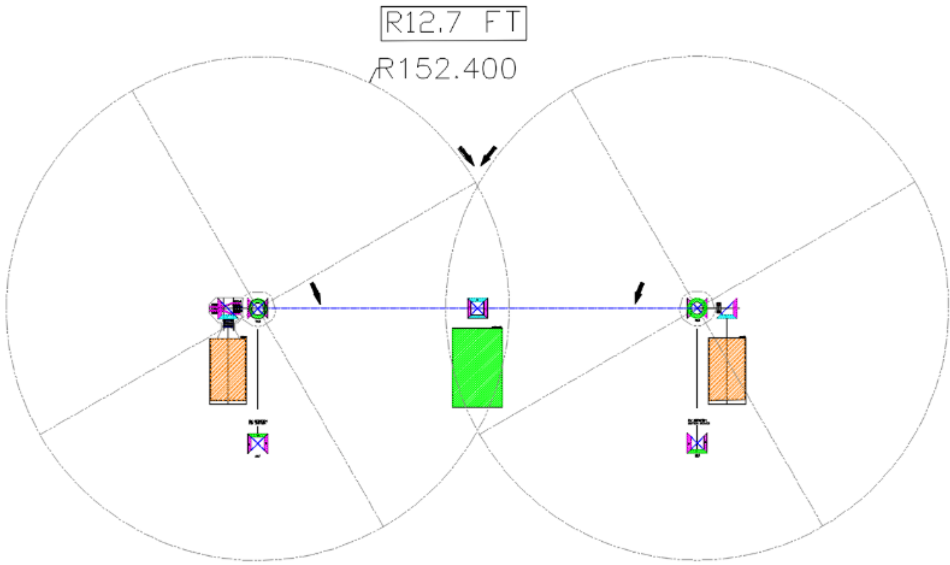

Figure 3.—Initial side-by-side baseline concept.

In order to proceed, the RVLT publications were assessed to collect information for sizing, shaft power, and component rotational speed definitions. Rotor speed(s) were determined from limiting rotor tip speed as was stated in RVLT concept vehicle literature. "*For low noise, the hover tip speed is much lower than conventional rotorcraft: 450 ft/sec for the quadrotor, 550 ft/sec for the Side-by-Side and Tiltwing. For efficient cruise, the Tiltwing operates at 50 percent hover tip speed*."

An initial CAD conceptual layout was created for the SbS-HE configuration that included a right-angle drive with integral overrunning sprag clutch at the engine (based on CH-47 twin-rotor twin-engine helicopter design) as is shown in Figure 3. The overrunning sprag clutch is necessary to disengage the engine in the event of an engine failure. The layout shown below also establishes the basis for shaft design.

The engine envelope (tan color, Figure 3) represents both the Rolls Royce RR300 and Allison 250/T63-A-5 as outlined in the NASA conceptual vehicle literature for the SbS hybrid vehicle. At this initial layout stage, the clutch at the motor-generator clutch was yet to be considered in any detailed manner.

Note that the above original work study layout shows the engines *outboard* of the rotor masts as does the RVLT SbS concept vehicle image (Figure 2). The SbS vehicle powertrain schematic of Figure 1 shows the engines *inboard* of the rotor masts, but such does not represent the detailed configuration arrangement used for this study.

Engine 2.—Stage Reduction Gearbox (Replacement Concept for the Initial One Dismissed)

As mentioned above, a new concept was developed for the initial reduction stage of a gearbox to interface to a turboshaft gas turbine engine in lieu of an integral reduction gear drive. This concept replaces the initial right-angle drive CH-47 based concept. This new concept corresponds to the SbS vehicle image (with engine depicted outboard of the rotor mast).

The new engine reduction gearbox concept is a two-stage configuration, the first stage being a parallel three shaft helical gear configuration with an idler gear to achieve both lateral offset between the engine and output shaft and desired output rotation. The second stage is a planetary gear train with input at the central sun gear (blue), ring gear fixed to ground (green), and output through the planet carrier. The concept advanced from a basic design layout is shown below in Figure 4.

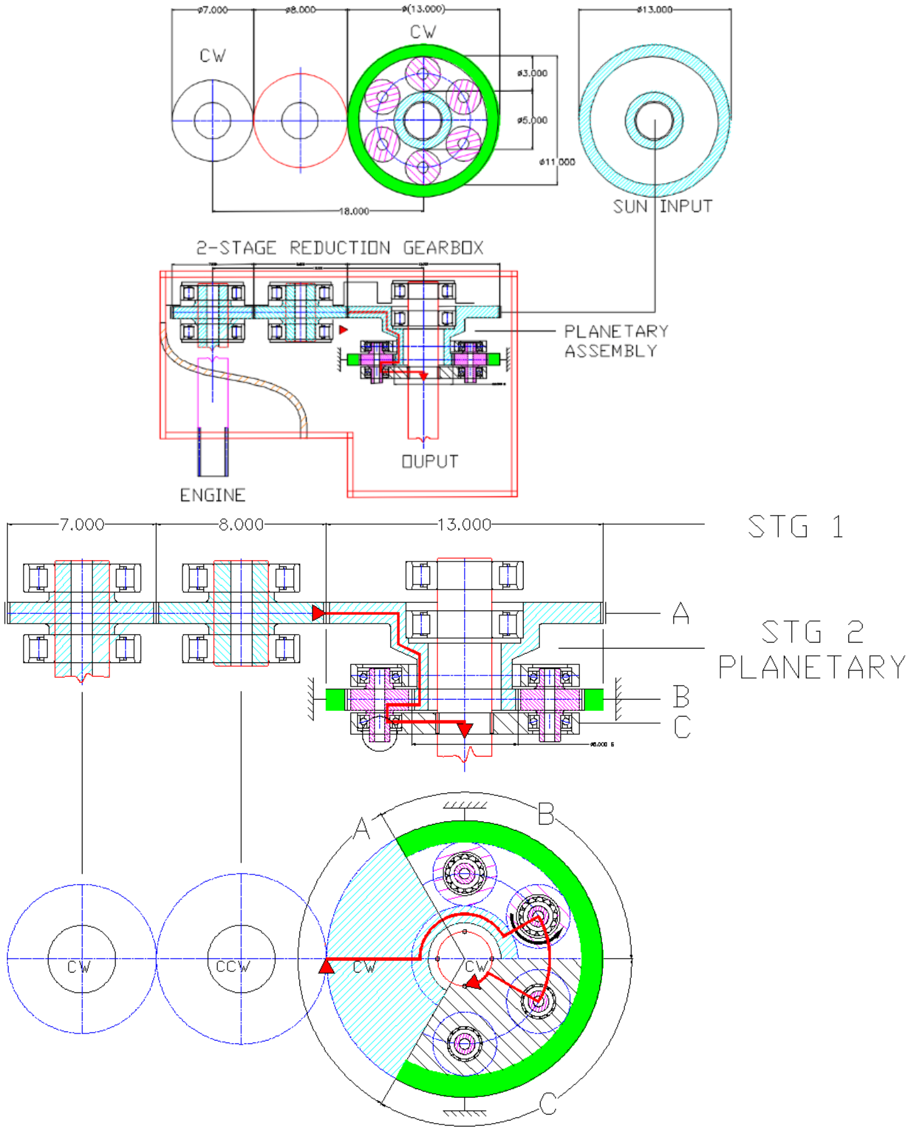

Figure 4.—Engine speed reduction gearbox.

Also, the integral overrunning sprag clutch of the reference CH-47 was replaced with a new concept and repositioned between the 2-stage reduction gearbox and the double right angle gear box, disconnecting both the engine and the above gearbox, separating the above from the pericyclic rotor drive while remaining connected to the cross-shafting. This enables one gas turbine engine and the motor-generator (motor mode) to provide power to both rotors in the event of a one-engine-inoperative (OEI) condition, permitting powered landing.

Overrunning Sprag Clutch at Gas Turbine Engine

The initial overrunning clutch concept was replaced with a new overrunning sprag clutch concept. Instead of being integral with the first gearbox, the new clutch concept is a separate component and enables easy positioning at other locations within the gear train for application to the subject SbS-HE vehicle and other powertrain configurations.

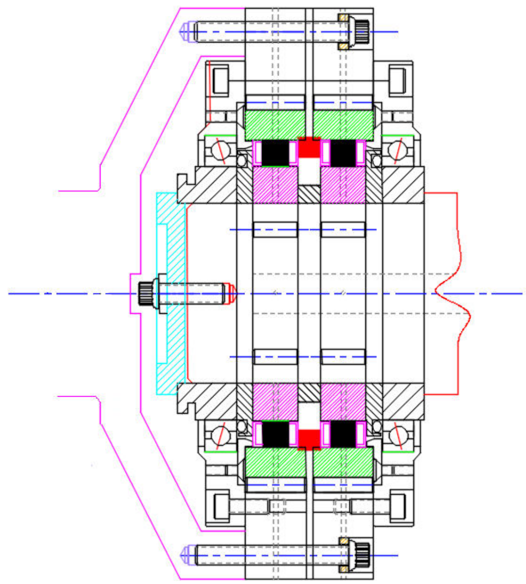

Figure 5.—Overrunning sprag clutch concept.

For the SbS-HE powertrain developed in this study, the overrunning sprag clutch is relocated between the initial 2-stage planetary reduction gearbox and a new concept single-input double-output bevel gearbox at the rotor mast. It should be noted that single-input is defined as engine output and dual-output is defined as rotor mast and cross shaft. In the event of an engine out, the power flow in the cross shaft is reversed from output to rotor input on whichever side experiences an OEI event. In the event of an OEI, the relocated overrunning clutch location not only disconnects the engine, but also disconnects the 2-stage gearbox, further reducing power drag during an OEI event.

The new concept configuration uses two sprag clutches in parallel as shown in Figure 5. The basic design is used on various rotorcraft. An overrunning sprag clutch with appropriate torque capacity for the SbS is the unit used in the NASA Two-Speed Drive. Power flow is from the left (engine), to the right (gearbox). The three primary sprag elements are outer race (green), sprag elements (black), and inner race (fuchsia). Power flow at the sprag is radially inward (i.e., green-black-fuchsia). Radially inward is simplification with respect to the 2-D image. In actuality, the power path has a tangential component to transfer torque. Lubrication is provided via a pressurized central lubricant passage in the shaft on the right.

Overrunning Sprag Clutch Torque Spike Attenuation

Overrunning sprag clutch engagement can result in significant torque spikes. In practice, torsional compliance and damping devices are sometimes included in powertrain systems to attenuate torque spikes associated with clutch engagement or dampen oscillatory (torsional) vibration modes.

A derivative concept of the above overrunning clutch incorporates integral torsion compliance and damping in the above configuration using multi-element polymer elements in series with the sprag elements. Damper elements are easily replaceable, and the configuration also enables installation of solid metal inserts for a research test configuration as a direct baseline comparison.

In Figure 6, the upper left shows the clutch assembly, axial section view, and the key parts exploded to the right: outer hub, retainer ring, outer race (green), inner race (fuchsia). In the lower right, the modified outer sprag race hub and retaining ring are shown.

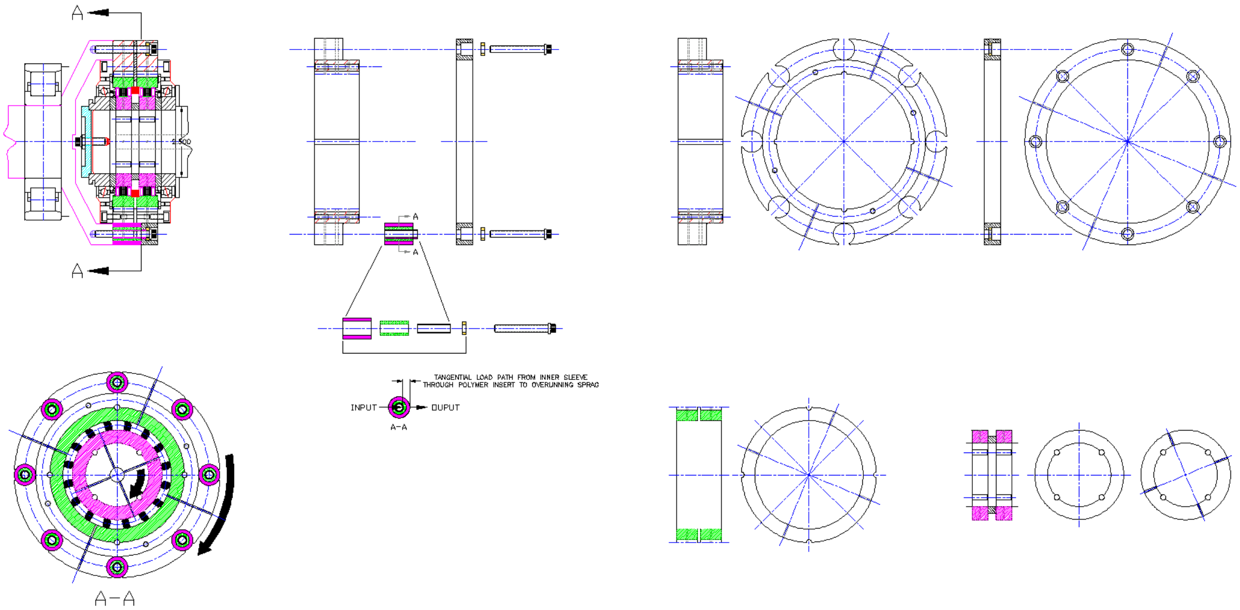

Figure 6.—Overrunning clutch torsional compliance concept.

The outer hub, in which the clutch outer race is mounted is modified by increasing the diameter of the original fastener attachment holes to mount eight polymer inserts at the fastener locations. Also, reducing the thickness of the outermost flange and introducing a retaining ring, occupying the space of the original outer hub, introduces a limited rotational degree of freedom. The combination of the above permits the hub with the polymer inserts to rotate between the output end of the driving shaft and the end retainer ring, and the force to be transferred through the polymer inserts through a tangential load path.

The polymer insert and related assembly parts are shown in Figure 7. The figure shown is a single overrunning sprag clutch as used in the NASA Two-Speed Drive (Ref. 5) in which the basic modifications discussed above are applied to the corresponding parts. This is a possibility for a developmental test bed that can be both easily and economically realized.

In Figure 7 power flow is from the red sectioned shaft flange transferring in parallel to the fasteners, then tangentially from the fasteners to the inner steel sleeves (clamped in compression), to the polymer inserts, next tangentially to the outer hub and outer sprag race assembly, then radially inward through the sprag elements, to the inner sprag race and output shaft assembly. Note that the hub in which the polymer inserts are installed is free to rotate between the driving shaft flange on the left and the combination retaining ring and aft bearing flange, with the driving forces (torque) transferred tangentially through the polymer inserts and radially inward from the outer sprag race through the sprag elements to the inner sprag race.

In other words, the small diameter longer metal sleeve is a precision matched length and is clamped between the driving shaft flange on the left and the combination retaining ring and aft bearing flange on the right, allowing the hub in which the polymer inserts are installed to be free to rotate between the outer flanges.

In the boxed view of Figure 7 the polymer inset loaded areas are shown, basically the inner and outer cylindrical surfaces. Note that in this view that the load applied to the polymer insert is shown being applied to the left.

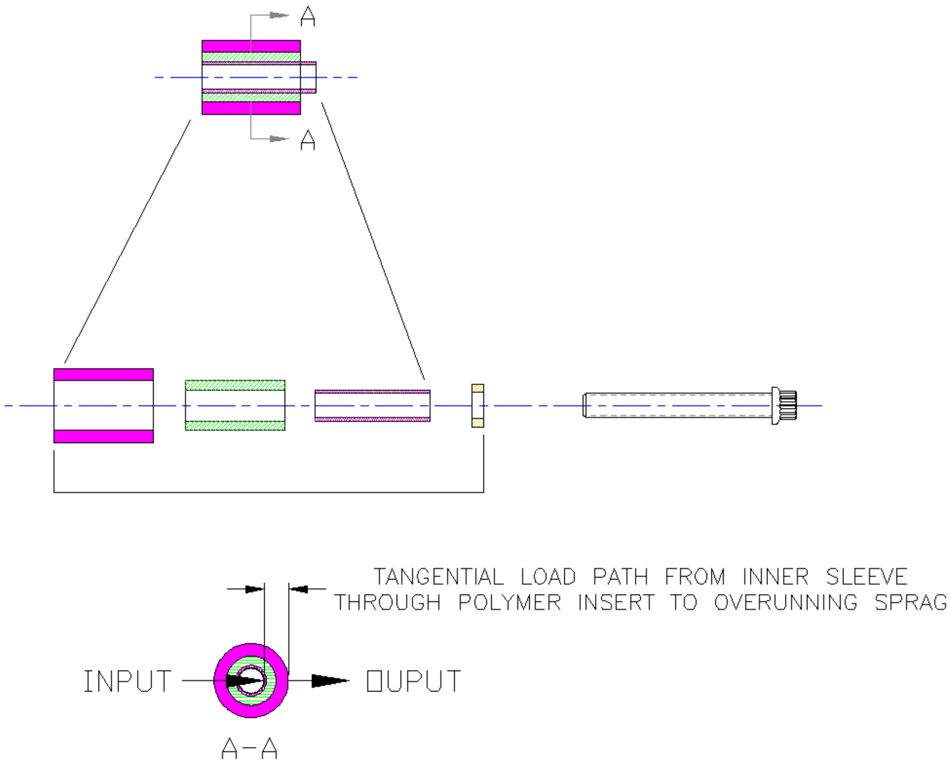

Figure 7.—Polymer insert assembly.

Attenuating engagement torque spike associated with an overrunning sprag clutch requires a study to develop a methodology to design the required degree of compliance and obtain the desired magnitude of torque spike attenuation, and ensure that no new torsional oscillatory vibration modes are introduced in the operating range. A method to design and manufacture tunable elements requires design and experimentation.

Double Right-Angle Drive Gearbox

The double right-angle drive gearbox connects the gas turbine engine GTE (input) to the rotor (output) and to the cross shaft (input/output). Refer to Figure 1 to Figure 3 that depict the gearbox locations and interconnections required for the SbS vehicle.

A concept layout for three shaft, single input, single input/output, single output, double right-angle gearbox was created and is located at the base of the rotor mast. The primary input to this gearbox is the gas turbine engine during normal operation, first passing through a primary reduction gearbox and an overrunning sprag clutch, then into this gearbox.

The second shaft is the primary output which is the input to a vertical rotor shaft that drives a pericyclic high reduction ratio drive. The second output becomes an input if the cross shaft is providing input power in the event of a single engine failure, (OEI). The cross shafts also provide power in/out to the motor dependent upon motor-generator operating mode.

The third shaft is a horizontal input/output that connects to the cross shaft, and a centrally located combiner gearbox, and the opposite side of the vehicle. This shaft path mechanically connects and synchronizes the rotation of the overlapping rotor blades that would clash and fail without timed synchronization.

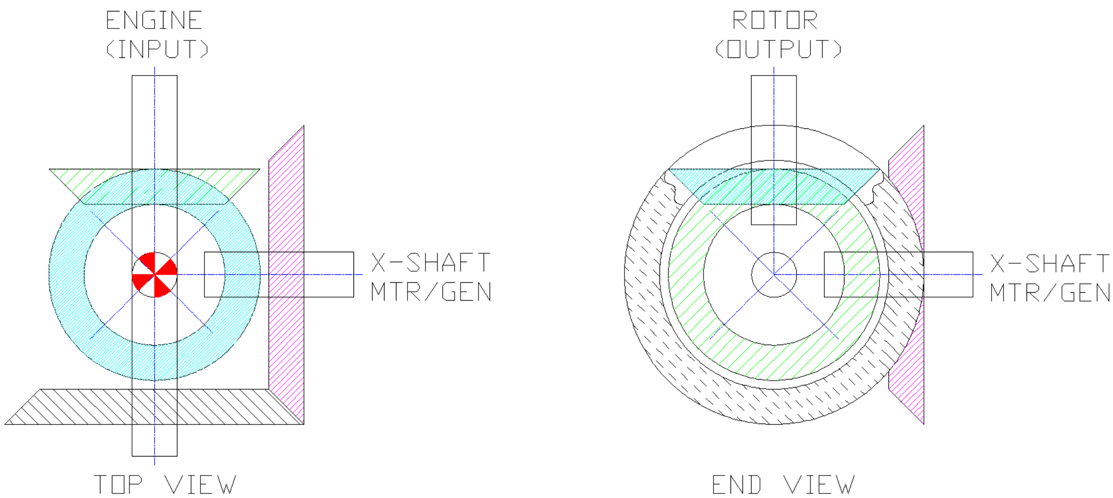

Figure 8.—Double right angle gearbox schematic (top view, rotor shaft out of page).

The conceptual single-input double-output right angle gearbox is shown in Figure 8. The engine input shaft mounts and drives two opposed bevel gears, each driving one of the two output bevel gears. The green bevel gear drives the blue bevel gear and is the input to the pericyclic rotor drive (red mini-rotor symbol at vertical axis out of the page). The larger black bevel gear drives the fuchsia bevel gear on the right, connected to the cross shaft.

High-Reduction-Ratio High Power Density Pericyclic Gear Drive

The SbS powertrain design requires a high reduction ratio gearbox located at the rotor mast. Locating the pericyclic drive stage as the last stage provides the lowest possible pericyclic input shaft speed, thereby minimizing both inertial and dynamic loads on internal bearings which are generally the critically loaded part of high-speed pericylic drives. This concept to be described is based on maintaining relatively high cross-shaft speed to minimize shaft diameter and weight as is common practice in helicopter powertrain designs using redundant cross-shaft power flow and is not unique to the SbS-He vehicle and not part of this study. The rotor-mast pericyclic drive configuration presented is a new concept derived from earlier pericyclic work.

The pericyclic gearing concept has been modelled and analyzed (Ref. 7) showing promise for high-reduction-ratio and power density improvements. However, the pericyclic drive concept needs hardware experimentation to validate its performance and elevate the technology readiness level. The pericyclic drive configuration has potential for providing both a high reduction ratio and high-power density, but a UAM pericyclic drive configuration is not available. Being familiar with the basic pericyclic drive geometry (Ref. 7), the pericyclic drive appeared viable as a potential rotor mast with an inline-vertical high-reduction gear train.

The basic pericyclic drive configuration used for the UAM powertrain design layout is based on a design developed by Penn State University (PSU) researchers (Ref. 7). Prototype hardware in development by PSU for test demonstration has a power capacity not far below the actual required power capacity for the SbS-He concept vehicle. Note that in previous work (Ref. 7) the pericyclic drive prototype is a parallel output shaft configuration, not an in-line configuration per this current work.

As stated, it was not immediately obvious how to integrate a pericyclic drive as a vertical rotor drive. A vertical input shaft configuration is the apparent best orientation although this orientation may not be

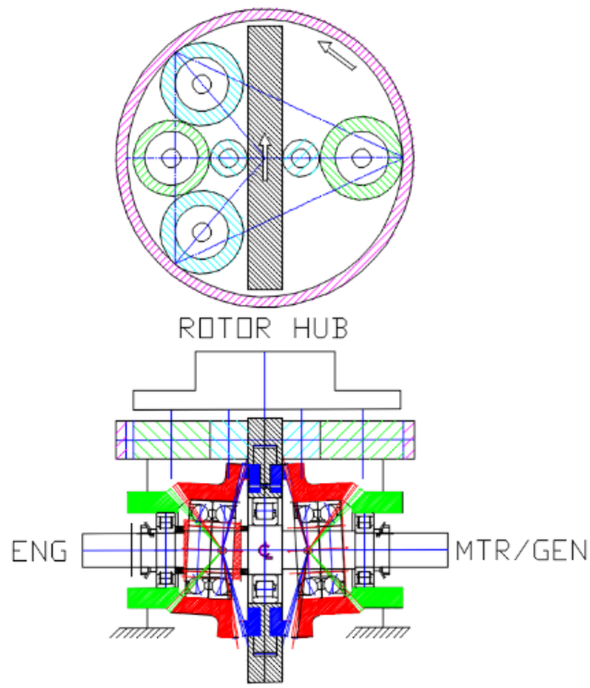

Figure 9.—Pericyclic rotor mast early concept with pericyclic horizontal orientation.

viable due to the pericyclic output drive gear being located between two stationary reaction gears. The PSU prototype pericyclic is a horizontal axis configuration where power output gear drives a laterally offset pinion on a parallel shaft. A lateral offset output is not unfavorable compared to an inline concentric configuration with a vertical axis. In addition to the stationary reaction gears being fixed to ground, these gears must be precisely angularly oriented to assure load sharing. Thus, the vertical input shaft orientation inline concentric drive may not be viable.

The concept of incorporating the pericyclic drive transitioned from the initial idea of a vertical axis to exploring a horizontal input shaft, requiring a right angle drive to obtain the vertical output to drive the rotor. A study to create and develop several concepts was attempted. The first concept was a horizontal input pericyclic drive and power output to a planetary gear train at the sun gear, with fixed carrier, and a concentric output through the ring gear. Use of a face gear drive as the pericyclic output gear in place of the output spur gear, as in the PSU prototype design, was considered and is shown in Figure 9.

A second concept for a horizontal input and vertical output drive utilized a double bevel gear as an alternate to the above, but such was also not viable. Creation of several other concepts to flush out a viable one did not result in any having merit to advance a horizontal input configuration.

Pericyclic Drive Split Power Inline Vertical Concept

Following the above a horizontal input pericyclic drive study not panning out, so revisiting the possibility of a viable vertical input shaft configuration was resumed. This time, the effort led to a new vertical input pericyclic drive concept that was judged viable. Figure 10 depicts a vertical input pericyclic drive split power output concept (shown with simplified engine motor-generator connections).

Following additional development, the above configuration was refined and is shown in Figure 11 as a side elevation (incomplete) and accompanied with possible top views. Power input is through the bottom with output flow through the central spur gear, and then split through either three or four parallel cluster gear-shaft assemblies, three possible configurations depicted as optional top views in the figure, and combining at the concentric rotor hub (black shaded). A key challenge in integrating the pericyclic drive as an inline concentric configuration is that the reaction gears (shown in green) are stationary, requiring the cluster assemblies to transfer power around the upper and lower reaction gears (fixed to the housing), then to the combining hub. A fixed three strut support for the static reaction gears was conceived that are positioned between the three countershaft gears. This is the preferred configuration due to the balanced loading with individual countershaft center spacing and the potential to equalize individual backlash between the three. Rotor speed for this concept arrangement is 415 rpm (550 ft/s tip speed).

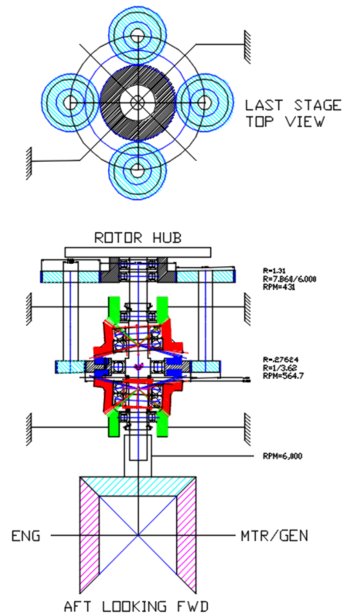

Figure 10.—Pericyclic rotor mast early concept with pericyclic vertical orientation.

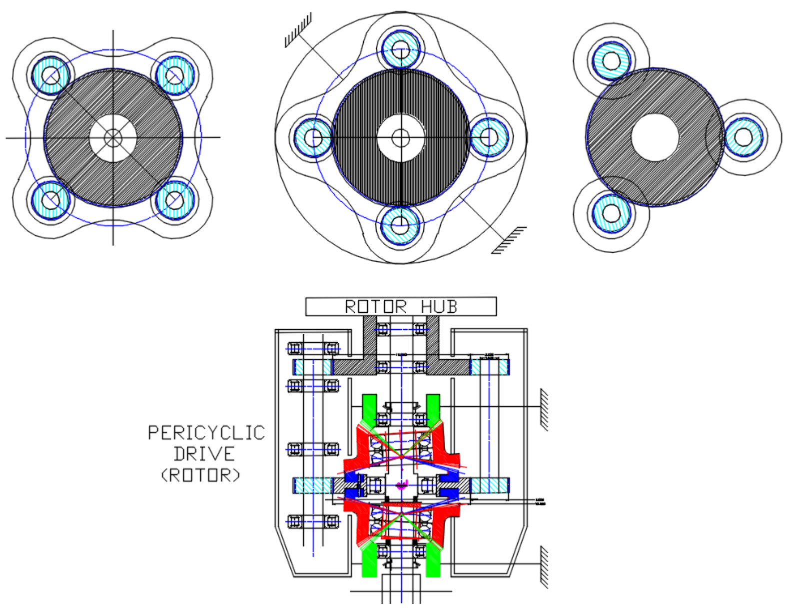

Figure 11.—Pericyclic rotor mast concept - pericyclic vertical + orientation countershafts.

Figure 11 depicts a vertical input pericyclic drive split power output concept where the number of countershafts was being considered and not yet addressing assembly of the countershafts with the central pericyclic gear train. The three views in the upper part of Figure 11 depict possible countershaft configurations under consideration.

The concept was refined such that the resulting rotor output is 431 rpm and a viable speed through the double right angle drive concept that is compatible with a motor-generator speed of 8,000 rpm (such number based on RVLT UAM information indicating that the motor/generator speed should be somewhere under 10,000 rpm). Also, the countershaft configuration options as shown above were evaluated, and a final selection was made for the three counter shaft configuration, as will be discussed later in more detail.

Benefits of Pericyclic Drive Concept for Application to UAM

The developed pericyclic drive was judged as having potential to provide the following benefits for the SbS-HE vehicle application:

- Vertical inline concentric input and output with anticipated favorable power density
- Multiple countershaft gears balance an unfavorable lateral load found in the PSU prototype
- The above also eliminates a large moment imposed on the input shaft from the pericyclic drive's pericyclic motion converter components (shown in red in Figure 11).
- Direct oil-jet lubrication and dry sump are viable (drains to double right-angle drive below)

Simplified cross sections of the current maturity of the concept pericyclic rotor mast drive highlighting the above benefits are shown in Figure 12 which depicts a vertical input pericyclic drive split power output concept. Further refinement of the concept was halted by advice and direction of project management. The concept now featured removable countershaft modular assemblies that enable equalizing the backlash and load share with the ability to vary the position of the countershaft centerline relative to the central input/output axis.

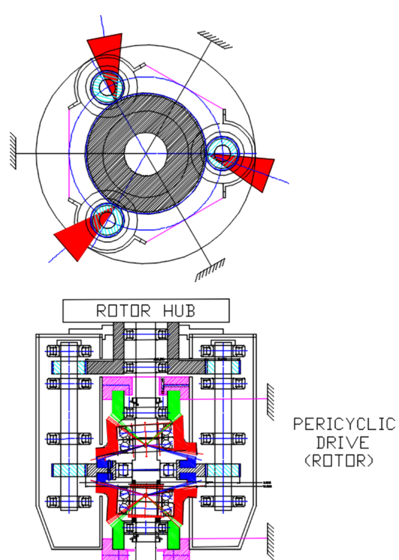

Figure 12.—Pericyclic rotor mast concept showing additional development.

With the above concept appearing viable, the initial component concepts were revisited individually. Revisiting component concepts devised earlier in the process is necessary to determine if they warrant further maturation or should be discarded and replaced with something new that is significantly different due to maturation of other components concepts for the system.

Combining Gearbox

The combining gearbox in centrally located between the two transverse cross shafts. This gearbox is a three-shaft input/output and is also connected to the motor-generator through the control clutch. This gearbox is a pass through for the cross shafts as well as enabling power flow, both input and output (to and from), the motor-generator. In normal cruise operation power flow is from the cross shafts to the motor generator to recharge the onboard batteries. In hover mode the combining gearbox enable power flow from the electric motor to the powertrain to contribute to the power required for hover mode. Also, in the event of one engine inoperable (OEI) event, this gearbox serves to route power from the single GTE to both rotors. In addition, it serves to route power to or from the motor generator dependent on operating mode. An OEI event requires that power flow is from the motor to supplement the overall power required for hover mode.

As a powertrain component, the combining gearbox serves normal functions of existing twin power input VTOL aircraft and is not a unique component to the SbS-He. Therefore, no detailed effort was expended on this component.

Motor-Generator Control Clutch

The motor-generator clutch power flow is bi-directional, therefore either the motor-generator must be connected such that it always spins (not favored in this study due to bearing reliability), or it is an on-off clutch, where it can be disengaged during engine start up, spun up and speed matched during engine idle warmup, and engaged during take-off hover mode. It can be disengaged during cruise and brought to rest or remain engaged and operated in generator mode to charge batteries. During the transition from cruise to hover, the motor-generator shaft speed is controlled to match the cross-shaft speed at the combiner gearbox via instrumentation, then the clutch is smoothly engaged with no slipping and without a torque spike. System studies should identify whether clutch control should be electric or hydraulic and should define the actual operation scheme as a system component.

Considered a required component for the hybrid-electric vehicle configuration, a concept layout was created for a controlled clutch at the motor-generator with power flow changes between hover and cruise flight modes (i.e., power assist during hover and generator mode during cruise). In addition, this clutch serves to disconnect the motor-generator from the powertrain during GTE start up. This clutch and two associated controls is a possible powertrain specific developmental test article.

A transmission study for another two-speed configuration for other than aircraft, not within the scope of clutch designs for the GRC two-speed experimental transmission, employed a clutch design considered suitable as the design basis for the SbS motor-generator control clutch.

During GTE start up, the engine is spun to idle speed with an integral starter, then fueled and ignited. During this operation, the motor-generator is disengaged from the powertrain. The motor is then rotated and spun up via on its own power. The conceived configuration employs speed sensors to enable synchronizing the motor-generator speed to the output speed from the combiner gearbox, prior to engaging the clutch, then increasing the motor torque to provide the additional share of the overall power required for hover mode by both the turboshaft gas turbines and the motor-generator. The concept and synchronous speed control provide a smooth connection and disconnection with minimal torque spike. In addition, motor-generator control is required to transition between motor and generator mode. The conceptual M-G control clutch is shown in Figure 13.

The engagement mechanism is shown isolated with more detail in Figure 14. Engagement is accomplished with a linear actuator that imparts circumferential motion (into the page) turning a hub (blue) supported on four rollers. The rollers ride on four circumferential ramps machined into the stationary base (black cross-sectioned area at far left). Turning the hub (blue) on the rollers/ramps imparts an axial translation and results in a clamping force on the centrally located friction/steel drive plates, which are alternately splined at the inside diameter and outside diameter respectively. The linear actuator can be either electric or hydraulic and the applied force is controlled by a pressure sensor to achieve the required clamping force at the drive plates.

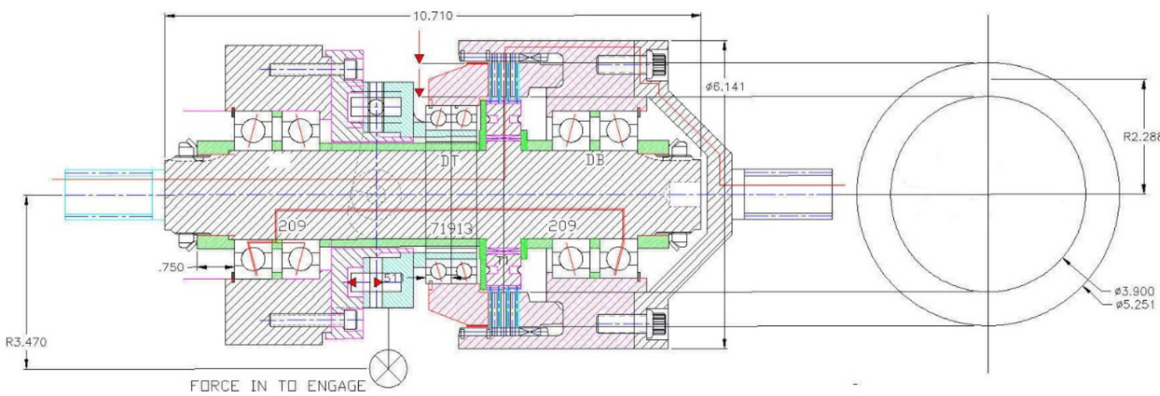

Figure 13.—Motor-Generator Control Clutch concept.

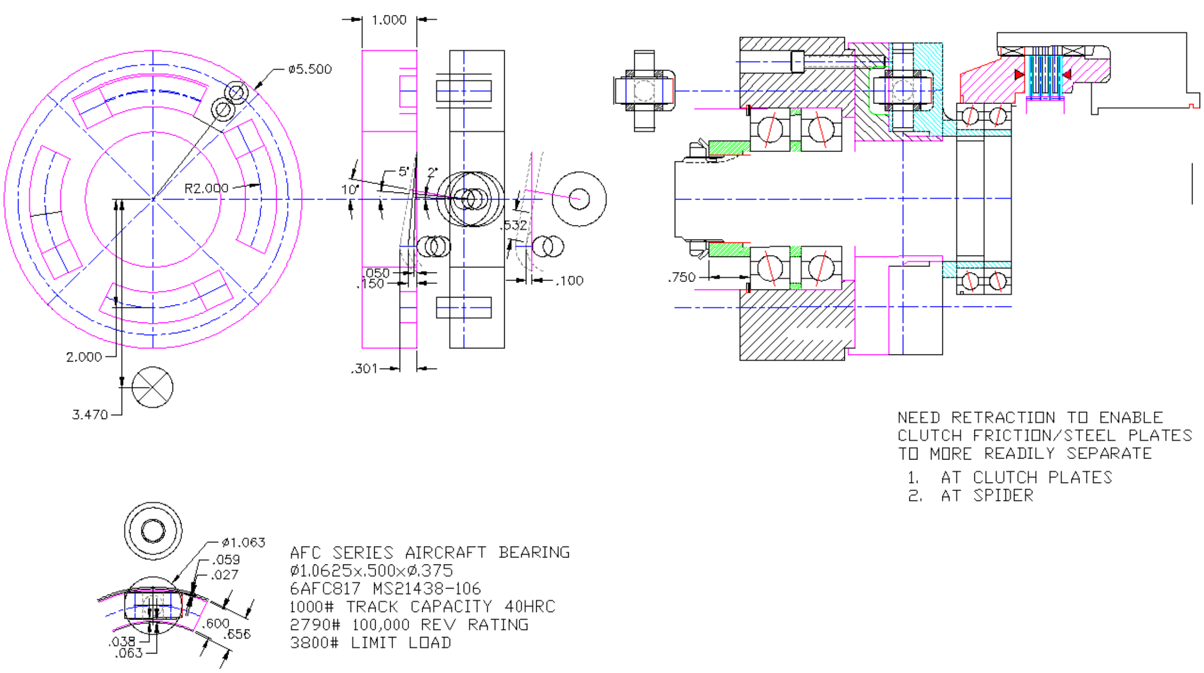

Figure 14.—Motor-Generator Control Clutch concept.

Overall Powertrain GTE to Rotor Mast

The combined engine reduction gearbox, double right angle drive gearbox (pericyclic rotor mast drive and cross-shaft drive) is shown in Figure 15. The sprag clutch completely disconnects the 2-stage reduction gearbox and engine in the event of a failure of either. This location is the best location for the sprag clutch. The engine envelopes are for the RR300 and Allison 250/T63-A-5, engines identified as suitable in the NASA conceptual vehicle literature for the SbS-HE.

SbS-HE Powertrain System Concept Design Layout

Incorporating the above individual component refinements and changes in interfaces, the above component concepts are combined in the SbS vehicle shown in Figure 16 and Figure 17.

In Figure 17 the green motor represents the physical size of the motor and the large rectangle represents the physical size of motor support hardware such as invertor, controller, thermal management. The aqua and fuchsia colored motors depicted away from the power train represent physical size of two different commercial motors with sufficient power for the overall power train.

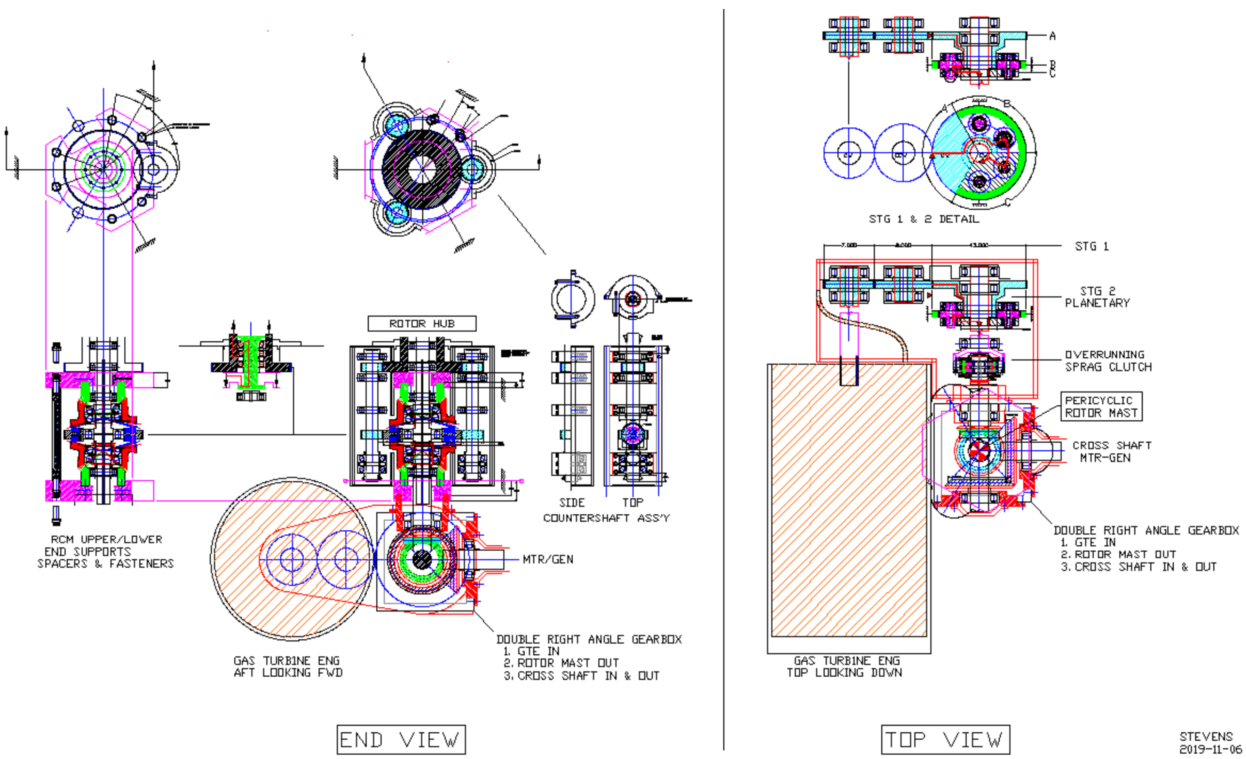

Figure 15.—Engine reduction gearbox, double right angle drive gearbox (pericyclic rotor mast drive and cross-shaft drive).

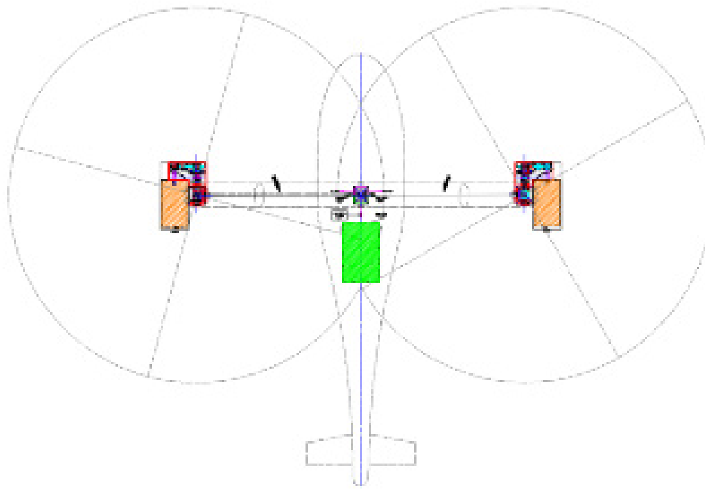

Figure 16.—SbS-HE Concept Propulsion Powertrain System.

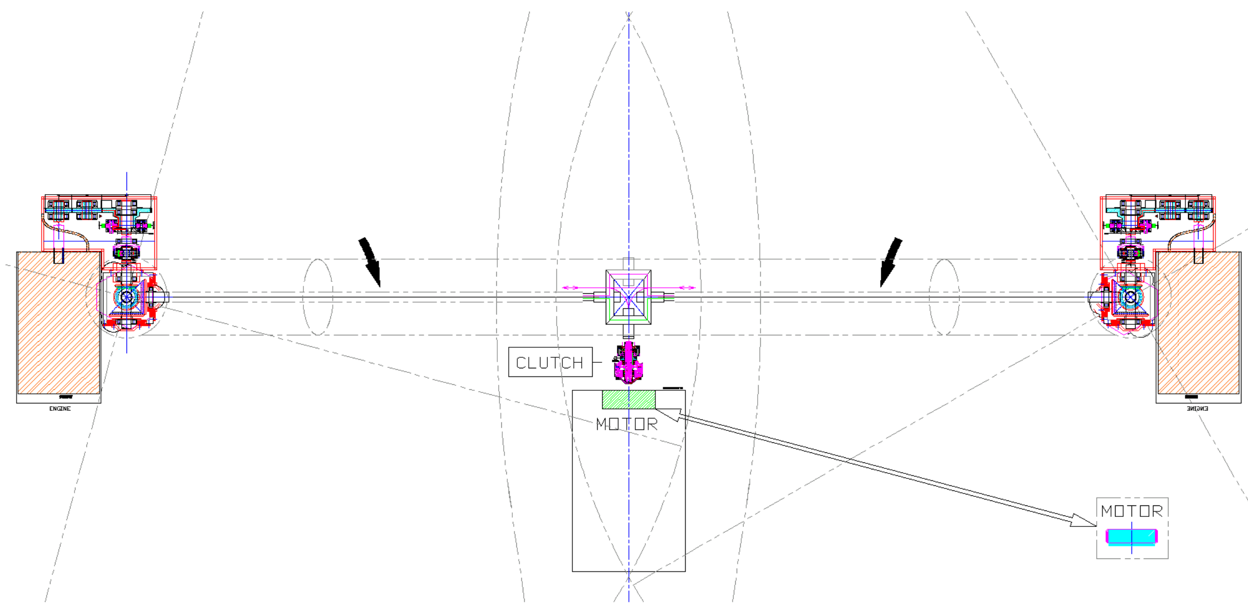

Figure 17.—SbS-HE concept propulsion powertrain system detail.

Section 3.—Candidate Facility and System Test Configuration for SbS-HE Powertrain and Others

A portion of a representative SbS-HE powertrain can be tested in the NASA Variable Speed Drive Test Rig with the addition of a facility combining gearbox, candidate flight motor test article(s), and key component test article(s) identified and discussed earlier. The overall size, power, and speed limitations of the existing facility was a consideration in devising potential UAM powertrain test capabilities. Figure 18 depicts the available test rig as was used for testing a two-speed ratio transmission. With rearrangements and added components, technologies for UAM vehicle powertrains can readily be tested and demonstrated.

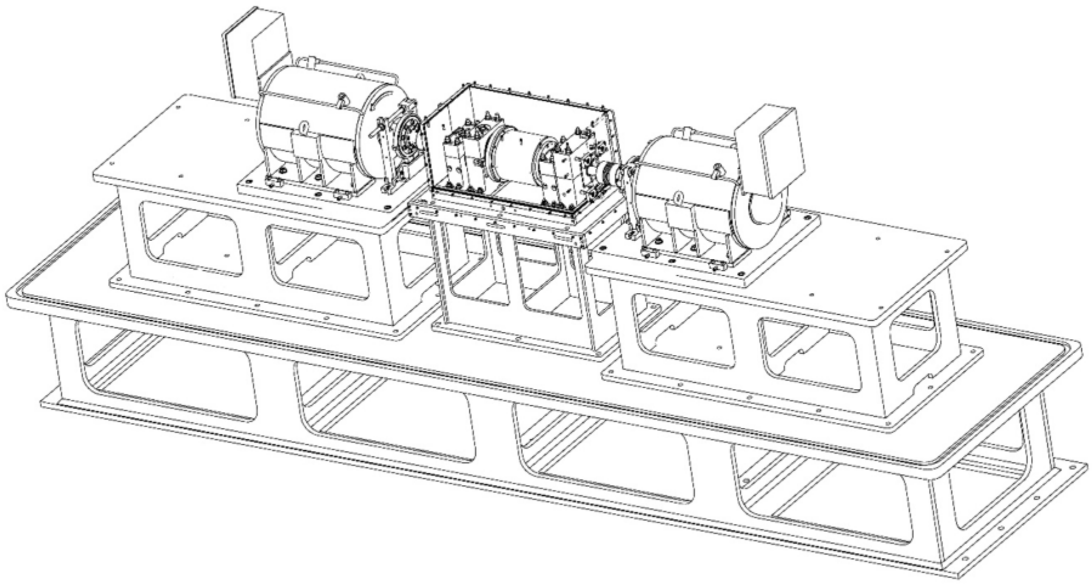

Figure 18.—NASA test facility for powertrains having electric machines capable of 150 kW (200 hp) continuous over the speed range 7500 to 15000 rpm.

One-half of the overall SbS-HE twin rotor powertrain can be represented in the facility in an all-electric simulation, from the gas turbine engine (GTE) to the rotor load with a coupled supplemental electric motor test article and a motor-generator control clutch. The system test could include a supplemental hover motor (prospective motors applicable for service in actual flight application currently being tested). The GTE can be simulated by the facility drive motor and the rotor load simulated by the facility load motor. In the current facility configuration, these motors are operated as a motor-generator pair using an electrically regenerative system. In addition, the supplemental electric motor is part of the UAM test configuration, the supplemental motor used both for hover power and also operated in generator mode during cruise to charge the flight vehicle battery storage (as could be simulated). Each of the three electric motors could be connected to the overall system through dedicated inline torque meters to measure loads during steady state as well as during transition between hover and cruise flight modes.

Universal Combining Gearbox (Possible New Enabling Facility Component)

The facility drive motor and supplemental hover motor are tied together via a new conceptual universal combining gearbox, a facility need as was identified in Section 1. The required combiner gearbox does not exist and will require both design and manufacture. The universal combiner gearbox is envisioned as a new flexible configuration with parallel input(s) and output(s) comprised of five offset shafts with spur gears and a 1:1 ratio. The design would have the flexibility of being able to utilize optional input and output shafts, inline or offset laterally, to enable multiple powertrain configurations to be tested. The input-output configurations may be dual input with single output, or conversely, single input with dual output, with three primary input and three output shafts located on three centerlines. Users can utilize the optional centerlines as required for a given test configuration.

Universal Combining Gearbox Input and Output Shaft Position Flexibility—Shaft Geometries

The end and center gears are mounted on input-output stub shafts, each with covers for the shaft extensions not utilized for a given configuration. Intermediate idler gears are supported on stub shafts and do have external extensions beyond the interior of the gearbox housing. The above enables employing the universal combining gearbox to readily represent multiple powertrain configurations.

In addition, the length of the overall test rig main support platform structure enables moving the facility drive and driven motor components over a wide range of locations/orientations and center distances enabling the ability to include long hollow shafts to include functions such as, a tunable torsional stiffness as well as the ability to test composite construction shafts or cross shafting under UAM operating load conditions. The combining gearbox and input-output power flow options are shown in Figure 19. Three of many possible power flow paths are shown in Figure 20.

Regardless of the RVLT concept vehicle powertrains that may be fabricated and tested, the combining gearbox concept can be a valuable component as a NASA facility asset to test other potential propulsion powertrain system configurations in the future. For the above reasons, the combining gearbox should be considered and further developed leading to either design-manufacture or direct procurement as a long-term facility asset for potential component tests such as high power magnetic motors/gear boxes, composite shafts, control components, torsional compliance components, and other novel components and technologies not yet identified.

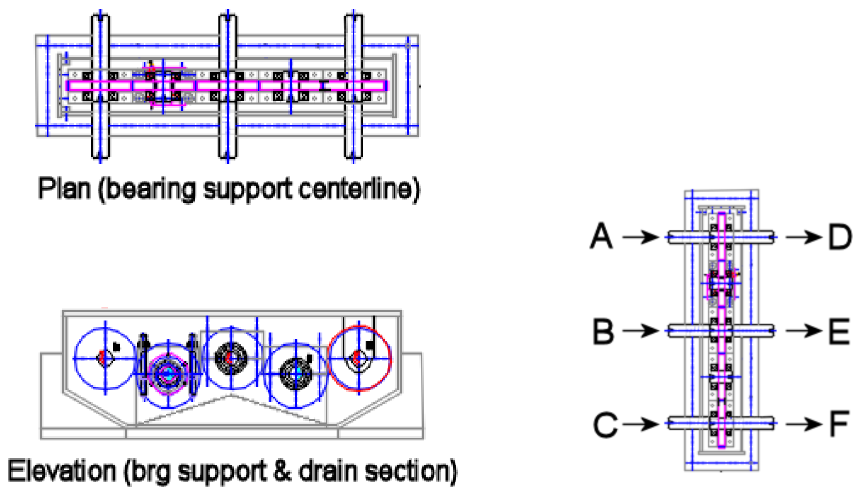

Figure 19.—Universal combining gearbox—elevation and plan views and power in/out.

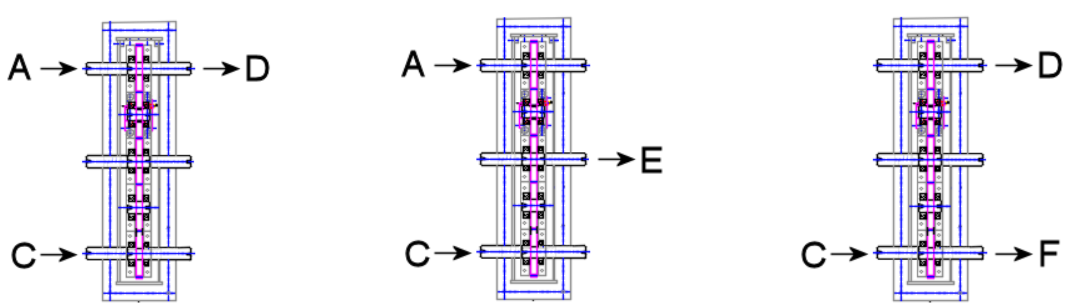

Figure 20.—Universal combining gearbox—example of power flow paths.

SbS-HE Powertrain Component and System Level Test Configurations at NASA Glenn Research Center

A concept test configuration for one-half of the symmetrical RVLT SbS-HE powertrain is shown Figure 21. The figure shows both a plan view and elevation view of the possible test configuration. This configuration enables tests of a proposed motor-generator (with inline torque meter) and the concept control clutch discussed earlier in this paper. The facility drive motor located in the upper left corner represents the gas turbine engine. The facility motor in the upper right is used as the rotor load. The supplemental electric motor for hover mode operation is located in the lower left corner and is connected by the motor-generator control clutch. Each motor has a dedicated inline torque meter. Those items of Figure 21 enclosed in green outlines or shown as green shaded items need to be designed and fabricated to enable such test capability.

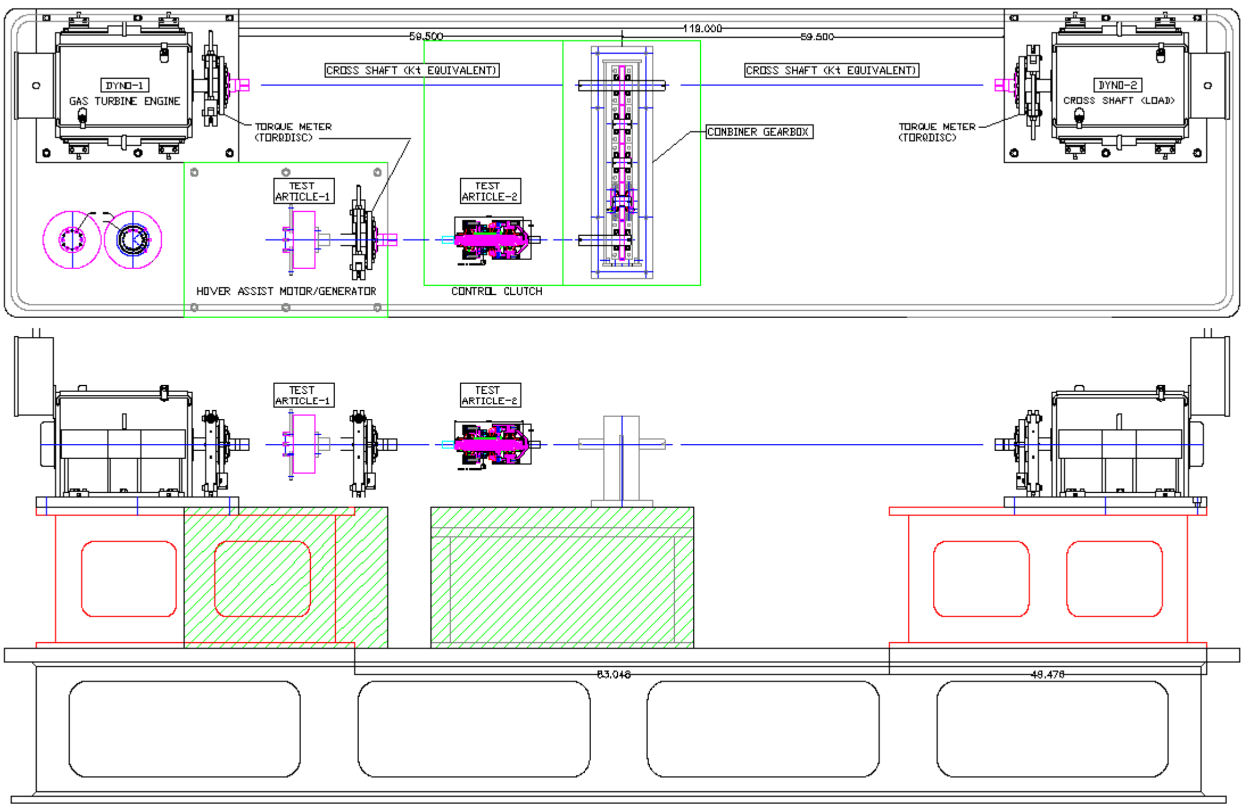

Figure 21.—SbS-HE powertrain component and system level test configuration, side elevation and plan views. Dimensions are shown in units of inches.

A notional flight mission for the SbS-HE concept vehicle was created and is shown in Table I. Although it is not possible to represent the total mission from start to end, flight simulation of various portions of the mission can be set up and simulated. Tests would focus on control and management of the transition between steady state portions of the mission and on the operation of component(s) such as the control clutch for the motor-generator (M-G) as well as transitioning between motor mode and generator mode.

The above test configuration and notional flight mission are a basis to simulate portions of the above notional flight mission, both steady state and transitions. The following can be simulated:

- Motor-Generator and M-G Control Clutch Control during Gas Turbine Start-Up and Transition to Hover (spin motor from rest to GTE idle speed and engage m-g clutch)
- Gas Turbine & Motor-Generator Power Share during Transition from Hover to Cruise (Control both GTE and hover motor speeds and switch Motor Mode to Generator Mode)
- Motor-Generator (Generator Mode) Power Generation during Cruise Mode
- Gas Turbine & Motor-Generator Power Share during Transition from Cruise to Hover (Transition Generator Mode to Motor Power Mode)
- Motor-Generator (Motor Mode) at test motor Full Power Output during Hover (Employing both Facility Motors as Load)

The first four simulations above can be accomplished with an initial set up. The last may require operational control reconfiguration and equipment movements.

TABLE I.—SbS-HE CONCEPT VEHICLE NOTIONAL FLIGHT MISSION

Flight Mode	GTE rpm	Comments
Start-idle	0 to 10000	(M-G decoupled from powertrain via m-g clutch)
Transition from idle to hover	---------------------	(M-G coupled to powertrain, motor mode)
Hover	15000	---------------------------------
Transition from GTE+M-G to GTE	---------------------	---------------------------------
Transition M-G from motor to generator	---------------------	---------------------------------
Cruise	15000 (+0/–15%[a])	(M-G, generator mode)
Transition m-g from generator to motor	---------------------	---------------------------------
Transition from GTE to GTE+M-G	---------------------	---------------------------------
Hover[b]	15000	---------------------------------
Idle[b]	10000	(M-G, generator mode)

[a]–15% via GTE operating rpm
[b]GTE idle speed 10,000, design speed 15,000

Other Possible Powertrain Component and System Level Test Configurations

Possible test configuration concepts representing other RVLT concept vehicle powertrains were studied. RVLT researchers are developing facility capabilities to emulate motors and loads that will enable the possibility of testing expanded configurations through emulation of parallel components or subsystems to represent more complete systems. Supplemental emulation can enable testing the entire system and introducing simulated faults in the physical powertrain or the opposite, introducing faults in the emulated potion of the powertrain and learning how to react to the programed faults. Figure 22, Figure 23, and Figure 24 show mechanical possibilities.

A test configuration can couple both facility motors to double load capacity to enable testing eVTOL power motors. Two configurations are shown in Figure 22 and Figure 23. The motors shown in phantom are locations for motor/generator test articles. In addition, this configuration can be used to test powertrain technologies such as composite shafts at double load capacity by utilizing the universal combining gearbox.

A configuration to test a portion of other eVTOL rotorcraft with cross shafting such as one-half of the overall powertrain of a Quad-Rotor or Tilt Wing aircraft can also be realized. Test Article 1, Test Article 2, and the cross-shafting could all be technology demonstration and development test articles using the configuration of Figure 24.

These test configurations just described could also be a part of a demonstrations of UAM vehicle propulsion systems encompassing more than only the rotating components. Within the same room are located a set of emulators that can be programmed to emulate characteristics of electrical equipment and can be arranged in a variety of configurations establishing a representation of the vehicle’s power grid. It is envisioned that the emulators can be used to emulate representative motors, generators, batteries and thereby research approaches and technologies for grid stability, fault recovery, and other such investigations of integrated propulsion systems.

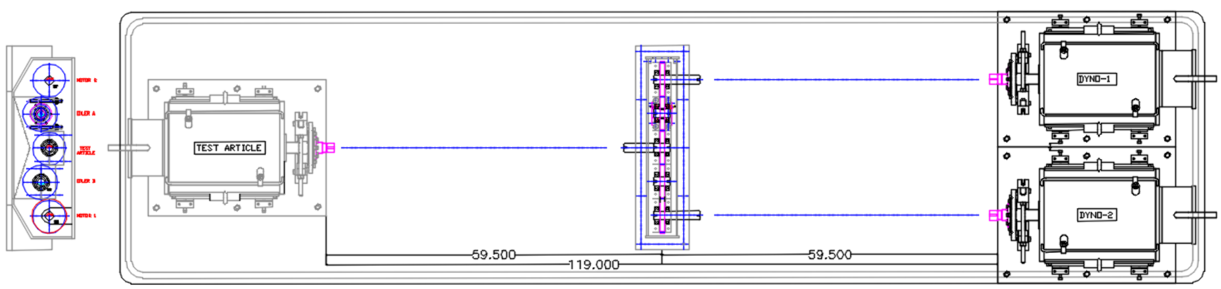

Figure 22.—Test motor and test components with 2x increased load capacity. Dimensions are shown in units of inches.

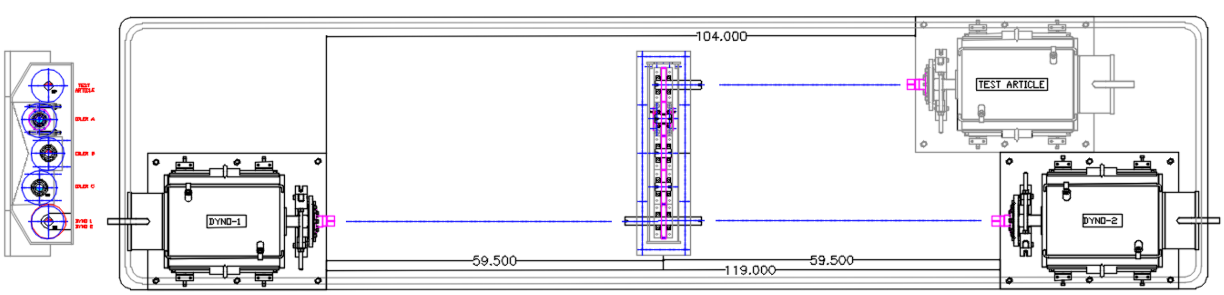

Figure 23.—Test motor and test components with 2x increased load capacity, alternate configuration. Dimensions are shown in units of inches.

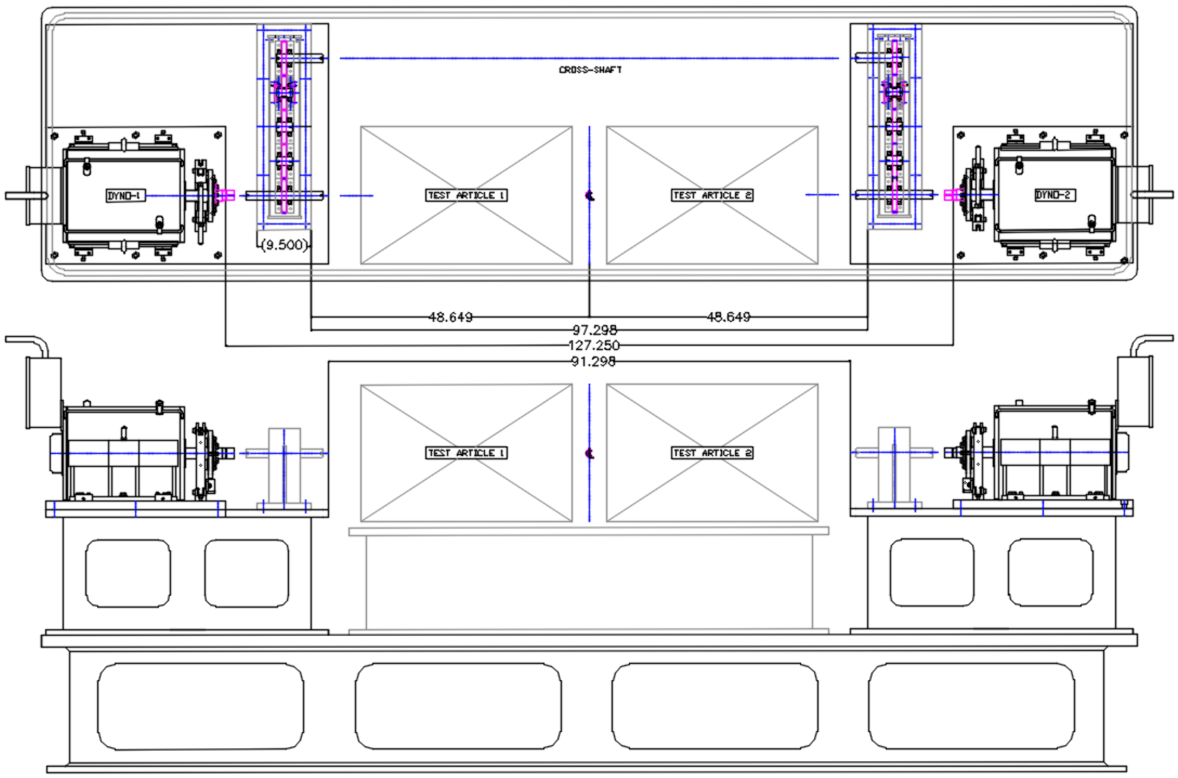

Figure 24.—UAM vehicle with cross shafting test layout for one-half of a powertrain of a Quad-Rotor or Tilt Wing aircraft. Overhead and plan views. Dimensions are shown in units of inches.

Summary

A conceptual hybrid electric-mechanical powertrain system was created for the SbS-HE concept vehicle that was comprised of mechanical components developed to a conceptual level of detail, and in a scale to enable possible test(s) at both component and system level at the NASA Glenn Research Center.

Two vehicle components were identified as being required for the SbS-HE propulsion system.

- Control Clutch (at Motor-Generator); does not include a positive mechanical lock
- Overrunning Sprag Clutch (at Engine); possible conceptual integral torsion attenuation

Several other vehicle components relevant to both RVLT SbS-HE and other concept vehicles, as well as general rotorcraft, were matured to a level sufficient for possible future consideration.

- RVLT Side-by-Side Hybrid Electric Concept Vehicle Propulsion Powertrain
- Primary 2-Stage Reduction Gearbox at the twin Gas Turbine Engines
- Right Angle Drive Gearbox (Engine Input—Double Output Rotor and Cross Shaft)
- Pericyclic Rotor Mast Gearbox (High Reduction Ratio and Low Mass)

One test facility component, the Universal Combining Gearbox, was identified to enable testing the RVLT SbS-HE and other hybrid electric powertrain components in system level tests as well as being a generic facility enhancement expanding facility utility for conventional powertrain components and system tests, as well as other test configurations not presently realized.

- Enable multiple RVLT concept vehicle powertrain configuration simulations.
- Enable dual input power powertrain configurations.
- Enable testing parallel driven components from a single drive motor.
- Enable testing of cross shaft pass through and motor-generator as drive and driven.

A notional powertrain for the SbS-HE vehicle was created, and this led to identifying some mechanical components for development and testing. Several components, both vehicle and facility, were identified for further work and investment for both vehicle development and for enhanced NASA testing capability.

NASA RVLT Project Management should consider the following recommendations to further the RVLT research capability and portfolio:

1. Design, model, and test the control of power transfer and sharing and power generation of the supplemental hover motor-generator to charge onboard batteries in a scale model test.
2. Development of the two key components identified for the SbS-HE concept vehicle (as well possible leveraging the other components identified during this study.
3. Advance the design of a high reduction ratio pericyclic drive (or other configurations, for example see Appendix) for application to eVTOL UAM vehicles. The pericyclic gearing basis of the prototype hardware could be utilized in the design of a direct oil-jet lubricated dry-sump rotor mast.
4. Execute a facility enhancement investment in a Universal Combining Gearbox for future powertrain component and system tests for both eVTOL UAM and conventional VTOL aircraft.

Appendix—Alternative Conceptual Propulsion Powertrain System for the RVLT Side-By-Side Concept Vehicle

In this report, a powertrain arrangement utilizing a pericyclic gearbox was conceived for the RVLT side-by-side hybrid electric concept vehicle. This concept vehicle is also sometimes referred to as a Lateral-Twin. During execution of the work herein, the Boeing Company, working via a NASA contract, also conceived of a powertrain arrangement for such a vehicle for the purposes of that contracted effort. The schematic of the Boeing-conceived powertrain (Figure 25, Ref. 4) is included here to provide interested readers convenient opportunity for comparisons of these arrangements.

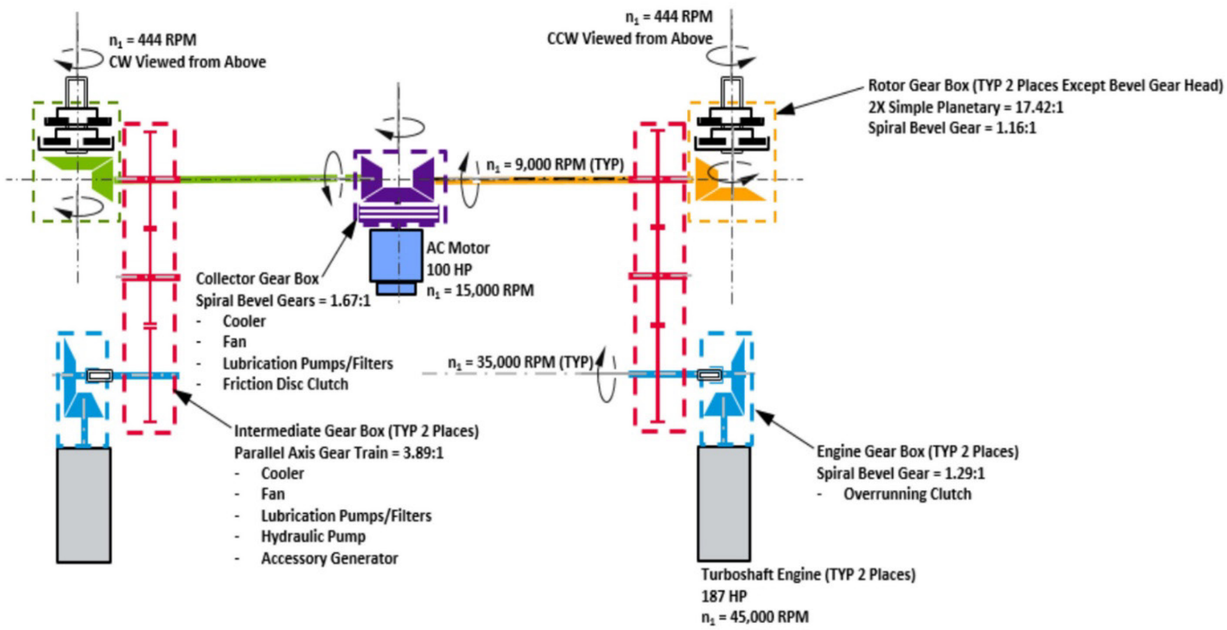

Figure 25.—Lateral-Twin Rotating System Schematic.

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