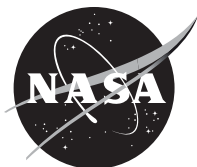NASA/CR—2019-220237

Composites for Advanced Drive Systems, A Systems Analysis—Revolutionary Vertical Lift Technology (RVLT)

Patrick R. Darmstadt, Mark J. Robuck, Robert F. Moore III, Scott H. Bouwer,
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The Boeing Company, Philadelphia, Pennsylvania

August 2019

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Acronyms

AH   Attack Helicopter
ARL   Army Research Laboratories
ART   Advanced Rotorcraft Transmission
CH   Cargo Helicopter
CPDD   Compound Planetary Differential Drive
ERDS   Enhanced Rotorcraft Drive Systems
FARDS   Future Advanced Rotorcraft Drive System
hp   Horsepower
IM   Intermediate Modulus
JMR   Joint Multi Role
LCTR2   Large Civil Tilt-Rotor
M   Boeing Helicopter Model
MH   Special Mission Helicopter
Mi   Mil Helicopter
NASA   National Aeronautics and Space Administration
GRC   NASA Glenn Research Center
NRTC   National Rotorcraft Technology Center
OEM   Original Equipment Manufacturer
OH   Observation Helicopter
PEEK   Polyetheretherketone
PMC   Polymer Matrix Composite
PSU   Pennsylvania State University
RAH   Reconnaissance and Attack Helicopter
RCM   Reaction Control Member
RITA   Rotorcraft Industry Technology Association
rpm   Revolutions per Minute
RTAPS   Research and Technology for Aerospace Propulsion Systems
RVLT   Revolutionary Vertical Lift Technology
SABP   Self-Aligning Bearingless Planetary
TRL   Technology Readiness Level
UH   Utility Helicopter
V   Vertical/Short Take-Off and Landing Vehicle

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Abstract

Rotorcraft propulsion systems are continually looking to improve power density; that is reducing weight and increasing power throughput. In order to advance rotorcraft propulsion system technology, NASA Glenn Research Center (GRC) contracted Boeing Vertical Lift (Contract #NNA15AB12B, Task Order NNA16BE07T) to perform system level benefit assessments for incorporation of composite materials into rotorcraft transmission gear and shaft systems, in the rotating frame. In general, the environment inside a typical rotorcraft transmission is aggressive for typical composite materials. Design challenges in the rotating frame and related safety risks must be understood and accounted for in the design.

Boeing developed a technical approach that evaluated a relatively large population of rotorcraft main transmissions. This technical approach took rotorcraft from various size classes and configurations and applied parametric weight estimating principles to assess the performance impact of composite hybrid technologies inside transmissions, in the rotating frame.

Parametric weight estimates showed that composite hybrid technologies account for an average 9 percent weight savings over the baseline transmissions. More weight savings may be observed when accounting for quantity of transmissions in an aircraft configuration and benefits to airframe, landing gear, and fuel systems. A weight reduction of 595 lb was calculated for NASA's Large Civil Tilt Rotor (LCTR2) by utilizing composite hybrid components inside the Prop-Rotor Transmission in the rotating frame and accounting for design changes to the airframe, landing gear, and fuel system.

In order to develop composite hybrid technologies, sub-scale and full-scale testing should continue, building on the work that GRC has begun. Design and testing efforts should focus on technical challenges, such as joint and attachment interfaces, temperature effects, inspection procedures, and fault detection. It is recommended to address technical challenges with targeted research and development efforts, conducted at relevant scale, prior to incorporating composite hybrid technologies within the rotating frame of helicopter transmissions.

1.0   Introduction

Throughout the aircraft industry, research initiatives have focused on reducing aircraft empty weight fraction. Specifically in rotorcraft propulsion systems, reducing weight, noise level, and lifecycle costs have been a primary focus for stand-alone research projects (Refs. 1 and 2) and for air-vehicle level design requirements. Additionally, future rotorcraft propulsion systems may levy speed changing technologies to increase forward flight speed and/or hover performance or may incorporate hybrid propulsion systems to reduce noise and operating costs (Ref. 3). However, both speed changing technologies and hybrid propulsion systems add weight to a conventional rotorcraft propulsion system. Boeing Vertical Lift, Philadelphia was contracted by NASA Glenn Research Center (GRC) (Contract #NNA15AB12B, Task Order NNA16BE07T) to perform a system study to estimate the weight savings of

composite hybrid drive system technologies to offset the increased empty weight fraction of speed changing or hybrid propulsion systems.

In order to meet GRC objectives a technical approach was developed that began with literature searches, initial assumptions, and material property assessments. Existing applications were investigated to build a foundation for further study and hypothesize technical challenges for implementation of composite materials; that is, typical transmission interfaces and operating environments are used to frame initial design challenges. Material data was used to characterize the inherent weight savings benefits of various material families. The final technical assessment collected the information from existing applications, initial technical challenges, and general guidance on material selection.

The developed technical approach would then continue using parametric estimating tools to estimate the weight of various transmission configurations and power-classes. Weights tables were generated for each configuration based on traditional materials and historical data which then began a conceptual design process for selected components to study design limitations of composite hybrid technology. Using component level weight estimates generated from the design process, a Special Features Factor was developed for each class of component. The Special Features Factor was then fed back into parametric estimates to include composite hybrid technology, characterizing the system level weight savings associated with composite hybrid technology.

This paper includes:

- Technical approach details, specifically to evaluate existing composite applications relevant to helicopter propulsion systems, typical transmission interfaces and operating environments, and material selection guidance.
- Transmission configurations selected for study and associated parametric weight estimates.
- Component design studies used for parametric weight estimates, including limited conceptual design and stress analysis to substantiate weight estimates. Note, composite hybrid components from other design activities or research projects are included in the data used to develop the Special Features Factor to increase confidence in the component design studies and to generate a larger database.
- Development of the Special Features Factor for parametric weight estimates including component design data from this study as well as component design data from related design activities or research projects.
- Updated parametric weight estimates to include composite hybrid technology. Parametric weight estimates use Special Features Factors developed using relevant design data to generate conservative weight estimates.
- Engineering challenges identified or revisited during the component design process. Design challenges requiring further technology maturation are addressed as well as production considerations and fail-safety.
- Summaries, conclusions, and recommendations for future work.

2.0 Scope

A systems level technical approach is developed in order to assess the performance impacts of introducing composite materials inside helicopter transmissions, in the rotating frame. Existing composite technologies, initially identified technical challenges, and established material selection and sizing techniques were used to develop the technical approach. In this approach transmissions from a multitude of rotorcraft configurations and power classes were studied to build a database of expected performance gains.

Conceptual design and stress analysis was performed to integrate composite materials into candidate components. Component designs were evaluated in order to provide a database for parametric weight estimating tools. The component designs are compiled and averaged with similar, existing designs in order to build a robust dataset for weight estimating purposes. A brief discussion on the estimated weight savings including weight savings impacts to the aircraft.

Using information developed during the component design phase, engineering challenges were identified and initial technical challenges refined. Recommendations for future work are provided to help guide the development process in years to come.

3.0 Technical Approach Background and Definition

A brief discussion on prior and current composite applications, typical transmission interfaces, and general material selection guidance is provided in order to characterize performance impacts of introducing composites inside helicopter transmissions and in the rotating frame and to recommend additional research that will introduce a greater use of composite materials into rotating, dynamic structures within the transmission. Composite materials provide beneficial strength and stiffness coupled with low density, which makes them appealing candidates for rotorcraft transmission applications. Rotating composite structures have been in use for decades in the rotorcraft industry, composite rotor shafts and sync shafts in tandem rotor helicopters, composite tail shafts in conventional helicopters, and cross shafts in tilt rotor helicopters. The noted applications utilize mechanical fastener joints to transmit torque and bending loads into and out of the composite structure and metallic spline connections to transmit loads between discrete assemblies. Rotating components inside rotorcraft transmissions are difficult applications for composite materials due to tight packaging, design features required to support gear loads, and high operating temperatures.

3.1 Composite Material Applications Within Rotorcraft Drive Systems

An axiom that affects the technical approach for this project is that most of the drive system weight is located in the low speed, high torque portion of the drive train. Drive systems are composed of many materials and components, with the steel components comprising over 50 percent of the weight in traditional drive system configurations. Composite rotor shafts, which are located at the high torque portions of the drive train and are most often made of steel alloys, offer great potential for weight reduction.

Boeing has been flying composite main rotor shafts for the past 35 years with the 234 aircraft, which are still in production. Composite rotor shafts were also featured in the flight tested Boeing Model 360 composite materials technology demonstrator. More recently Boeing has been developing a fiber placed carbon composite version of the CH-47 (D, F, and G model) Aft Rotor Shaft for use in an upgraded drive system (Ref. 4), which will potentially be in production in the 2020 timeframe.

Composite tail shafts have been featured in conventional helicopters, such as the RAH-66 Comanche (Ref. 5). More recent tail shaft applications include a ballistic tolerant thermoplastic design for the CH-53K King Stallion (Ref. 6) and ballistic tolerant sync shafts for the CH-47F (Ref. 7).

Within the propulsion system, helicopters have been producing composite rotor blades for decades. The CH-47 first fielded composite rotor blades with the first flight of fiberglass rotor blades c. 1978 (Ref. 8).

To develop technology for applications inside the gearbox, research activities have included characterization of hybrid gear performance in a sub-scale ryder gear test (Ref. 9). Full-scale hybrid gear fabrication and testing has demonstrated manufacturability and load carrying capacity of a composite gear web attached a steel gear rim (Ref. 1). Polyetheretherketone (PEEK) bearing cages have been used in

programs such as the Future Advanced Rotorcraft Drive System (FARDS) Program, demonstrating functional capabilities in 140 percent overload conditions (Ref. 10). Oil-out testing during the FARDS Program demonstrated operational capability of PEEK cages for approximately 40 min in an oil-out condition. The test was stopped prior to a catastrophic failure and post-test inspection of the gearbox found that the PEEK cages had melted (Ref. 10).

3.2 Mechanical Transmission Interfaces and Operating Environments

Mechanical power transmission is currently the preferred method of large-scale rotorcraft to transfer mechanical power from a rotorcraft s' engines to rotor systems of large-scale rotorcraft. Mechanical power is typically supplied by turboshaft or internal combustion engines requiring both speed reductions and redirected torque paths from the horizontal output shaft of the respective engine to vertically mounted main rotor heads or tail rotors mounted far from the engine.

Typical rotorcraft drive systems include 3 to 6 transmissions and interconnecting shafts, each transmission changing the direction of the applied torque and/or reducing shaft speed through bevel or parallel axis gear meshes. Each bevel gear or parallel axis gear requires features to support bearings, react preload, or transmit power to or from a mating gear or shaft. Typical examples of these features on metallic gear shafts include integral bearings races, mechanical screw threads, and spline arrays. Figure 1 shows two (2) typical bevel pinions with gear teeth, splines, bearing journals, an integral bearing race and mechanical screw threads. One bevel pinion is classified as an "overhung" configuration, where the gear head extends out beyond the bearing set, analogous to a cantilever beam. The other bevel pinion is classified as a "straddle" mount design, where the gear head is placed between two (2) bearings that react radial loads, analogous to a simply supported beam. The features required for safe transmission operation have historically been difficult to incorporate into composite hybrid structures.

Operating machinery inside rotorcraft transmissions can also create high temperature environments. Typical design temperatures for rotorcraft transmissions are 300 °F continuously, with transient requirements for oil out conditions. Ryder gear testing in low lubrication or no lubrication conditions (Ref. 9) creates temperatures that could limit the selection of composite materials based solely on the high temperatures observed with two (2) steel gear in mesh. However, the referenced ryder gear testing (Ref. 9) showed that a tested hybrid pancake gear meshing with a steel pancake gear did not enter an unstable temperature rise. Testing was discontinued after 145 min of run time at increasing load levels.
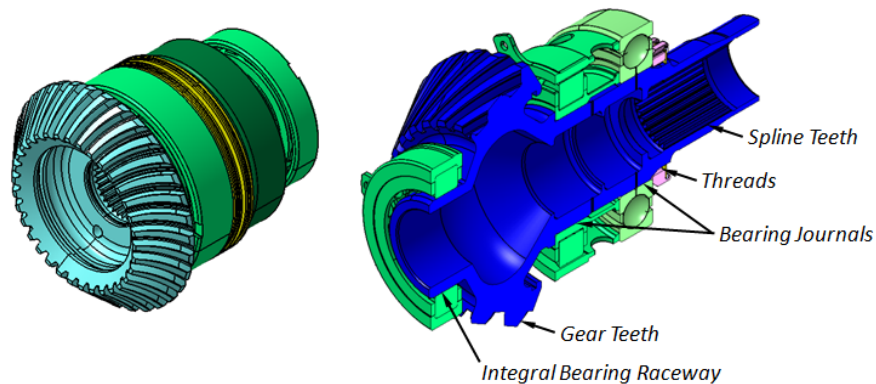
Figure 1.—Typical Overhung Gear (Left) and Cross-Section of Straddle Mounted Gear (Right).

3.3   Material Selection Discussion

In general, drive system or transmission configuration design tasks begin with initial component sizing and layouts to identify critical features, initial weight estimates, etc. Initial sizing and layouts typically leverage experience or past design history to make conservative design decisions with limited information available about loading, lubrication, etc. Although some uses of composites have made their way inside the highly stressed, stiffness critical environment internal to rotorcraft transmissions, limited design experience is available to understand if integration of composite structures inside transmissions will lead to performance benefits required to buy their way onto an aircraft. The following section applies an existing material selection method (Refs. 11 and 12) to shaft designs that are critical in strength or stiffness.

Transmission shafting is typically governed by bending or torsional strength or stiffness. Mathematical functions have been derived to correlate strength and stiffness to density (Ref. 11). Candidate materials for shaft designs may then be down-selected grouped by the material index, M. Specific strength, M_s, and specific stiffness, M_d, are derived as functions of allowable stress, σ, and density, ρ, and of tensile modulus, E, and density, ρ, respectively.

$$M_s = \frac{\sigma^\beta}{\rho}$$
(1)

$$M_d = \frac{E^\beta}{\rho}$$
(2)

Note, β accounts for variations in load conditions. Maximizing the specific strength or specific stiffness will conceptually provide the lightest weight design. This method assumes that design features of a specific application will be similar to each other, irrespective of material choice.

First, specific strength for torsion and bending are developed. Isolating a shaft's ability to carry bending load, a shaft's required diameter, d, me be written as a function of applied moment, M, and allowable normal stress, σ, by rearranging the equation for bending stress.

$$\sigma = \frac{M}{Z}$$
(3)

$$Z = \frac{I}{c} = \frac{\frac{1}{64}\pi d^4}{\frac{1}{2}d} = \frac{1}{32}\pi d^3$$
(4)

$$\sigma = \frac{32M}{\pi d^3}$$
(5)

$$d = \sqrt[3]{\frac{32M}{\pi} * \frac{1}{\sigma}}$$
(6)

Additionally, the weight of a component, W, is a function of volume, V, (which is a function of Area, A, and length, L) and density, ρ.

$$W = V\rho = AL\rho = \left(\frac{1}{4}\pi d^2\right)L\rho \tag{7}$$

$$W = L\pi^{1/3}\left(4M\right)^{2/3}\left(\frac{\rho}{\sigma^{2/3}}\right) \tag{8}$$

Similarly applied torque may be used to characterize the weight of a shaft section as a function of principal stress, σ, and density, ρ. Assuming pure torque, the shear stress, τ_{max}, is equal to the maximum principal stress, σ_1, and the cross sectional area, A, may be written as a function of maximum principal stress by rearranging the equation for shear stress, τ_{max}. Weight, W, may be written as a function of the material properties, density, ρ, and stress, σ.

$$\tau_{max} = \sigma_1 = \frac{Tr}{J} = \frac{16T}{\pi} * \frac{1}{d^3} \tag{9}$$

$$W = L\pi^{1/3}\left(2T\right)^{2/3}\left(\frac{\rho}{\sigma^{2/3}}\right) \tag{10}$$

Length, L, moment, M, and Torque, T, are considered to be constants. The specific strength, M_s, for both bending and torsional strength has been shown to be:

$$M_s = \frac{\sigma^{2/3}}{\rho} \tag{11}$$

where $\beta = 2/3$. Conceptually, minimizing $\rho/\sigma^{2/3}$, or, inversely, maximizing the specific stiffness, M_s, will provide the lightest weight design. Figure 2 shows a plot of tensile strength, σ, as a function of density, ρ, with $\beta = 1/2$ material index lines overlaid (Ref. 12). Figure 2 overlays the specific strength, $M_s = \sigma^{2/3}/\rho$. Composites, ceramics, and titanium alloys make good candidate aerospace grade materials for lightweight shaft designs based on strength. Aluminum alloy is also shown to have a similar specific strength to titanium alloy, but the maximum specific strength of titanium is slightly greater than that of for aluminum alloy.

Bending stiffness may also be characterized by deriving cross sectional area, A, as a function of an applied mid-span force, F, moment of inertia, I, and length, L, by manipulating the equation for bending deflection (Ref. 11).

$$\delta = y_{max} = \frac{FL^3}{3EI} \tag{12}$$

The spring constant, k, is:

$$k = \frac{F}{\delta} = \frac{3EI}{L^3} = \frac{3E}{L^3}\left(\frac{1}{64}\pi d^4\right) = \frac{3E}{l^3}\left(\frac{A^2}{4\pi}\right) \tag{13}$$

$$A = \sqrt{\frac{4\pi k L^3}{3E}} \tag{14}$$

The weight of a component, W, is a function of area, A, length, L, and density, ρ. The function for area, A, may be substituted to manipulate weight to be a function of material properties, ρ, and tensile modulus, E.

$$W = L\rho\sqrt{\frac{4\pi k L^3}{3E}} = 2\sqrt{\frac{\pi k L^5}{3}}\left(\frac{\rho}{E^{1/2}}\right) \tag{15}$$

Similarly, torsional angle of deflection, θ, may be used to create a relationship between stiffness and weight.

$$\theta = \frac{TL}{GJ} = \frac{4\pi TL}{GA^2} \tag{16}$$

$$A = \sqrt{\frac{4\pi TL}{G}} \tag{17}$$

Again, the weight of a component, W, is a function of area, A, length, l, and density, ρ. The function for area, A, may be substituted to manipulate the weight to be a function of material properties, ρ, and torsional modulus, G, which may be approximated as a function of ρ and E.

$$W = 2\sqrt{\pi TL}\left(\frac{\rho}{G^{1/2}}\right) = 2\sqrt{2\pi TL}\left(\frac{\rho}{[E(1+\nu)]^{1/2}}\right) \approx 2.25\sqrt{2\pi TL}\left(\frac{\rho}{E^{1/2}}\right) \tag{18}$$

Length, L, spring constant, k, and Torque, T, are considered to be constants. The specific stiffness, M_d, for both bending and torsional stiffness has been shown to be:

$$M_d = \frac{E^{1/2}}{\rho} \tag{19}$$

where $\beta = 1/2$. Again, minimizing $\rho/E^{1/2}$, or, inversely, maximizing the specific stiffness, M_d, will provide the lightest weight design. Figure 3 plots the specific stiffness, $M_d = E^{1/2}/\rho$, of selected materials (Ref. 12). Composites, ceramics, and aluminum alloys make good candidate aerospace grade materials for lightweight shaft designs based on bending stiffness. Figure 3 shows a plot of tensile modulus, E, as a function of density, ρ, with $\beta = 1/2$ material index lines overlaid (Ref. 12). Composites, ceramics, and aluminum alloys make good candidate aerospace grade materials for lightweight shaft designs based on torsional stiffness.

Table 1 summarizes the three (3) top material candidates mentioned above for each strength and stiffness design requirement. As can be seen in Figure 2 and Figure 3, composite and ceramic materials have fundamental material properties that make them intriguing candidates for lightweight gear shaft design applications. Engineering challenges are identified later in this report with more detail, including non-recurring challenges such as schedule risks in major programs and technical challenges requiring additional research prior to implementing a composite hybrid design internal to a transmission. Table 1 shows isotropic materials (specifically ceramics, titanium alloys, and aluminum alloys) that may also be introduced for substantial weight savings with arguably less engineering challenges associated with each isotropic material. Conversely, ceramics and other high strength metals tend to be more brittle in nature, which reduces their appeal when considering damage tolerant designs or time-to-failure after a flaw (manufacturing, handling, or other) initiates a crack in a safe-life design.

TABLE 1.—SUMMARY OF CANDIDATE AEROSPACE MATERIALS

Candidate material family ranking	Strength	Stiffness
1	Composites	Composites
2	Ceramics	Ceramics
3	Titanium Alloys	Aluminum Alloys
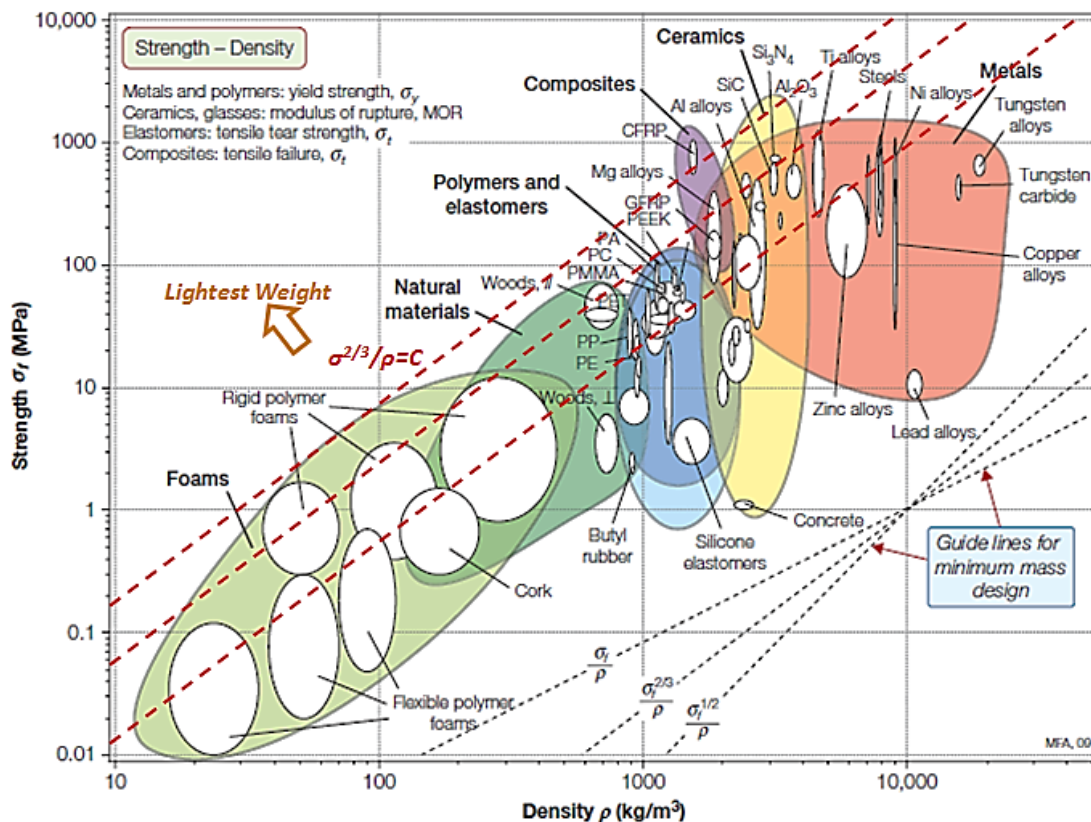
Figure 2.—Specific Strength for Material Selection Guidance (Ref. 12).
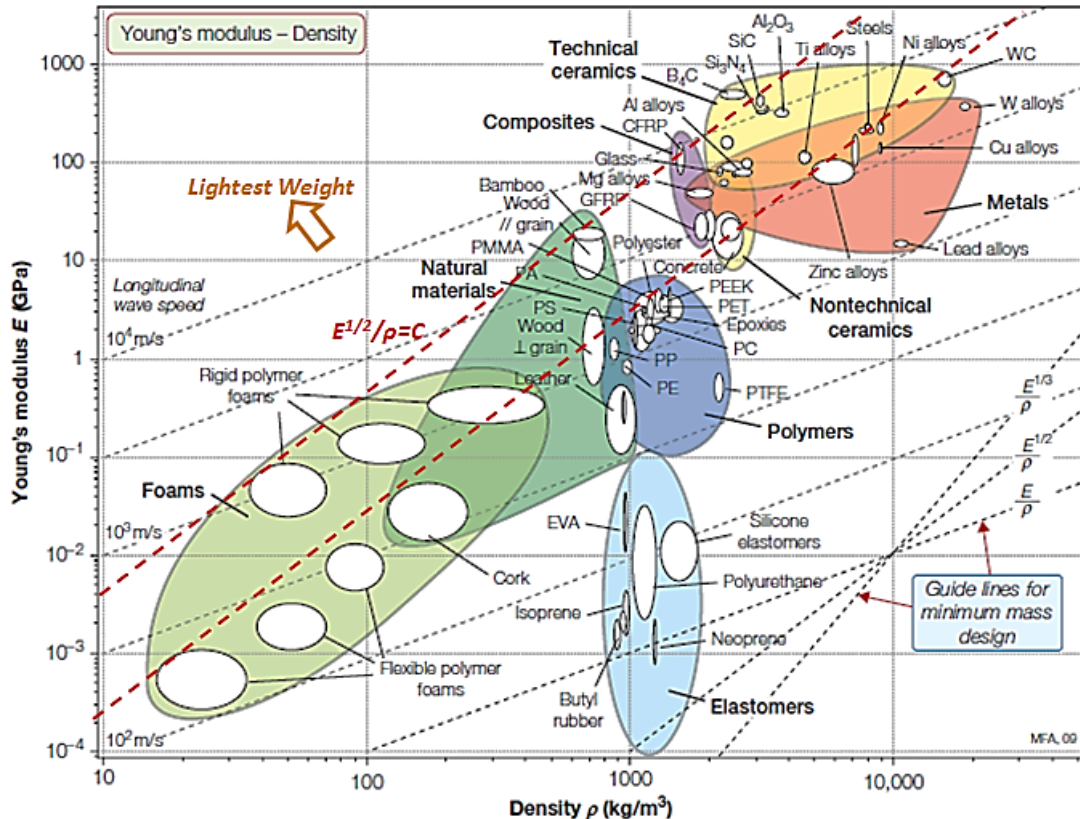
Figure 3.—Specific Stiffness for Material Selection Guidance (Ref. 12).

3.4 Technical Approach Definition

Limited history exists incorporating composite components inside of a transmission system on a large scale, see Section 3.1. Due to this limited history, it is difficult for OEMs to quantify a weight savings benefit early in an aircraft's development, when limited design data is available. Typically, preliminary weight estimates are developed from existing aircraft configurations. Simple diagrams with very little design detail are developed into parametric weight estimates to produce aircraft weight parameters. This may be problematic when trying to introduce new technologies into sub-systems that have long procurement times, such as drive systems. Early program decisions may limit the introduction of new technology because a quantifiable performance benefit may not be available during initial sizing.

A systems level technical approach was developed based on the information presented in Sections 3.1 through 3.3 in order to increase the accuracy of parametric weight estimates with composite hybrid transmission components. The primary objective of the technical approach was to develop Special Features Factors for components fabricated with extensive use of composites. The Special Features Factor could then be applied to parametric weight estimates of a variety of transmission configurations in order to develop parametric weight estimates of composite hybrid transmissions early in an aircrafts' development program. The technical approach to develop the Special Features Factor consisted of seven (7) segments, as follows:

1. Define baseline transmission configurations;
2. Parametric weight estimates;
3. Develop weights tables and block diagrams;
4. Design hybrid composite components;

5. Update weights tables;
6. Develop Special Features Factor;
7. Incorporate Special Features Factor into parametric weight estimates.

Segment 1 gathered horsepower, input shaft speeds, and transmission gear ratios for both existing transmission configurations and new transmission configurations. This information fed Segment 2 where weight estimates were developed for transmission configurations of various types and power classes. Segment 3 developed weight breakdowns so that weight deltas at the component level could be incorporated into parametric weight estimates and developed block diagrams to represent new design(s).

Segment 4 consumed the most resources through the course of the program. Detailed component designs were developed for baseline configurations and hybrid composite configurations. Weights tables and weight deltas were then updated (Segment 5) with the weight difference and the weight difference fed Special Features Factor development (Segment 6) and later parametric weight estimates (Segment 7). An 8th segment was also included to define technical recommendations and follow-on research recommendations. This segment utilized supporting design data from component designs and prior research and was not used to develop a Special Features Factor, so it is considered a separate activity from Segments 1 to 7. A graphic of the technical approach was developed with intent to clearly communicate how each segment supported one-another, see Figure 4.

This approach combines information developed for parametric estimating, typically early in an aircrafts inception, and incorporates design information to feed data back to the parametric estimates. Future aircraft programs may be able to benefit from the development of the Special Features Factor to reduce empty weight estimates early in an aircraft's lifecycle.
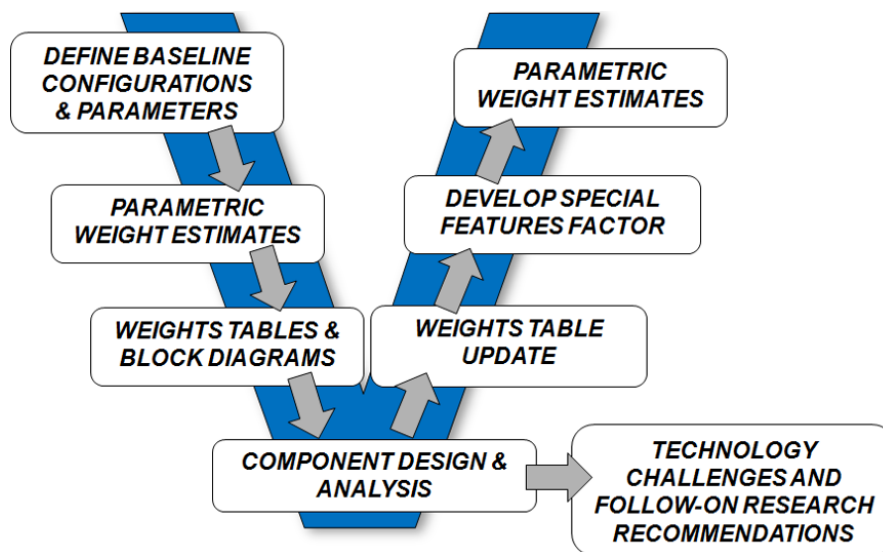
Figure 4.—Technical Approach Graphic.

4.0   Baseline Transmission Configurations

A wide variety of transmission configurations were selected for parametric weight analysis. Simple and compound planetary systems, transmission configurations for tilt rotorcraft, large bull gear reductions, and a nutating reduction (Ref. 13) were included in the parametric weight study. A total of 16 transmissions or reductions were analyzed, including the Russian Mi-26 main transmission. Table 2 summarizes the transmissions selected for this study and lists the input power and input and output shaft speeds for quick reference.

Publically available information was used to define the technical parameters of each configuration. Some values presented were derived as part of this study as described in following sections.

5.0   Parametric Weight Estimates and Block Diagrams

Parametric weight estimates were developed for the baseline transmission configurations from Table 2. Data utilized to develop the parametric weight estimates came from publically available sources. Assumptions were made and/or trade studies were performed to develop a reasonable parametric weight estimate if data required for parametric weight estimates was not available.

One engine inoperable (OEI) conditions were not included in parametric weight estimates. Unless otherwise specified, housings were considered to be fabricated from magnesium and typical gear steels were used for gears, shafts, and planet carriers. Unless other specified, gears were assumed to be straddle mounted, see Figure 1.

Baseline parametric weight estimates were used as a basis for comparison against drive system weights with extensive use of composite hybrid materials.

Initial investigations resulted in the hypothesis that configurations with large bull gears would result in the largest weight savings. It was believed that the web area of large bull gears with limited mechanical interfaces would lead to large weight savings. Transmission type classifications were based on this assumption, grouping many configurations with bull gears and planetary systems into the "Large Bull Gears" type category. Additionally, a Bull Gear Block Diagram was developed to show how a blank sheet of paper configuration may benefit from composite hybrid components during aircraft initial sizing efforts, when parametric weight estimates drive program decisions. The Bull Gear Block Diagram was sized for multiple power classes.

Each weight estimate uses shaft power, gear ratios, transmission assembly support factors, bearing support factors, housing factors, and special features factors to develop a parametric weight estimate.

Power-Speed Index is used to characterize transmission classes based on speed reduction and power throughput. For this study, the index is based on transmission input speed and transmission output speed. The Power-Speed Index is calculated as follows:

$$\text{Index} = \frac{(\text{hp})^{0.76} (\text{input rpm})^{0.13}}{(\text{output rpm})^{0.89}} \qquad (20)$$

where, index is the power-speed index, hp is the power throughput, Input rpm is the input speed of the transmission, and output rpm is output speed of the transmission.

TABLE 2.—TRANSMISSION CONFIGURATIONS IDENTIFIED FOR ENGINEERING STUDY

Type	ID	Title	Input power, hp	Input speed, rpm	Output speed, rpm	Power-speed, index
Simple Planetary	A	CH-47F Block II Aft Transmission	4,960	6,912	225	16.4
	B	OH-58 Main Transmission	270	6,200	354	1.2
Compound Planetary	C	RITA Compound Planetary Transmission	5,000	6,912	225	16.5
	D	Compound Planetary Differential Drive	5,720	2,419	212	16.8
	E	SABP Transmission	450 (Demo)	33,350	348	2.2
---------------------	F	Proprietary Transmission Configuration	(1)	(1)	(1)	19.1
---------------------	G	PSU Pericycler	5,000	5,485	225	16.0
Prop-Rotor Configuration	H	LCTR2 Prop-Rotor Transmission	8,125	15,000	191	30.5
	J	V-22 Prop-Rotor Transmission	5,011	15,000	397	11.0
	K	Bell ART II Transmission	5,011	15,000	397	11.0
Large Bull Gears	L	Bull Gear Block Diagram	(2)	7,000	225	(2)
	M	AH-64D Main Transmission	2,828	9,841	289	9.0
	N	RAH-66 Main Transmission	2,400	23,000	355	7.3
	P	UH-60 Main Transmission	3,400	5,750	258	10.6
	R	CH-53K Main Transmission	22,500	14,708	178	70.2
	S	Mi-26 Main Transmission	19,725	8,300	132	77.0

Notes: Input and output data is Boeing Proprietary. Normalized values are provided in the form of a power-speed index. Configuration "L" is parametrically estimated at three (3) different power levels. Refer to Configuration "L" description and assumptions.

5.1 Configuration A—CH-47F Block II Aft Transmission

The CH-47F Block II Aft Rotor (Aft) Transmission dates back to the first flight of the CH-47A c. 1960. Although design changes have been made, most notably the CH-47D Drive System Redesign, the configuration remains largely unchanged. The CH-47F Block II Program increases the power throughput requirements, but keeps the transmission configuration similar to prior CH-47 Models. For this study the Aft Rotor Shaft and the Aft Transmission were considered one unit, even though in practice, the Aft Rotor Shaft may be removed from the Aft Transmission.

The CH-47, being a tandem rotor helicopter, has a corresponding Forward Rotor (Forward) Transmission which is similar to the Aft Transmission, with small changes in accessory locations and rotor shaft incidence angles. Percent weight savings calculated for the Aft Transmission may be expected to be similar to the Forward Transmission, although the Forward Rotor Shaft poses greater design challenges being a one-piece steel design with an integral planet carrier.

The Input Bevel Gear Mesh transmits power into the first Stage Sun Gear. The Sun Gear Meshes with the 1st Stage Planetary Gear Set which mesh with the Fixed Ring Gear and is interconnected to the 1st Stage Planet Carrier. The 1st Stage Planet Carrier transmits power to the 2nd Stage Sun Gear which meshes with the 2nd Stage Planetary Gear Set which mesh with the Fixed Ring Gear and is interconnected to the 2nd Stage Planet Carrier. The 2nd Stage Planet Carrier is splined into Aft Rotor Shaft Assembly.

Potential Composite Material Applications

Figure 5.—CH-47 Aft Transmission Weight Group (Includes Aft Rotor Shaft).

- Power/Speed Data:
  - Input Power: 4,960 hp
  - Input Shaft Speed: 6,912 rpm
  - Output Shaft(s) Speed: 225 rpm
- Power-Speed Index = 16.4
- Components Included in Parametric Weight Estimate
  - Bevel Gear Mesh
  - 1st Stage Planetary Set
  - 2nd Stage Planetary Set
  - Aft Rotor Shaft
- Assumptions:
  - Straddle mounted bevel pinion and gear
  - Magnesium housings
- Potential Composite Material Applications:
  - Rotor Shaft
  - Planet Carriers
  - Bevel Gear Shafts

5.2   Configuration B—OH-58 Main Transmission

The OH-58 Kiowa is a US Army Scout helicopter. The OH-58A was fielded in the early 1980's and has gone through multiple upgrade programs before its retirement c. 2015. The main transmission configuration studied for this project is from the original, OH-58A, which is similar to the commercial Bell 206 Jet Ranger. The OH-58A is a single-engine helicopter.

The single Input Pinion meshes with the mating Bevel Gear. The Bevel Gear is splined into the Sun Gear Shaft which meshes with a Planetary Gear Set. The Planetary Gear Set meshes with a fixed Ring Gear and are interconnected to the Planet Carrier. The Planet Carrier is splined into the Rotor Shaft (Ref. 15).

- Power/Speed Data:
  - Input Power: 270 hp
  - Input Shaft Speed: 6200 rpm
  - Output Shaft(s) Speed: 354 rpm
- Power-Speed Index = 1.2
- Components Included in Parametric Weight Estimate
  - Bevel Gear Mesh
  - Planetary Set
  - Rotor Shaft
- Assumptions:
  - Straddle mounted bevel pinion and gear
  - Magnesium housings
- Potential Composite Material Applications:
  - Rotor Shaft
  - Planet Carrier
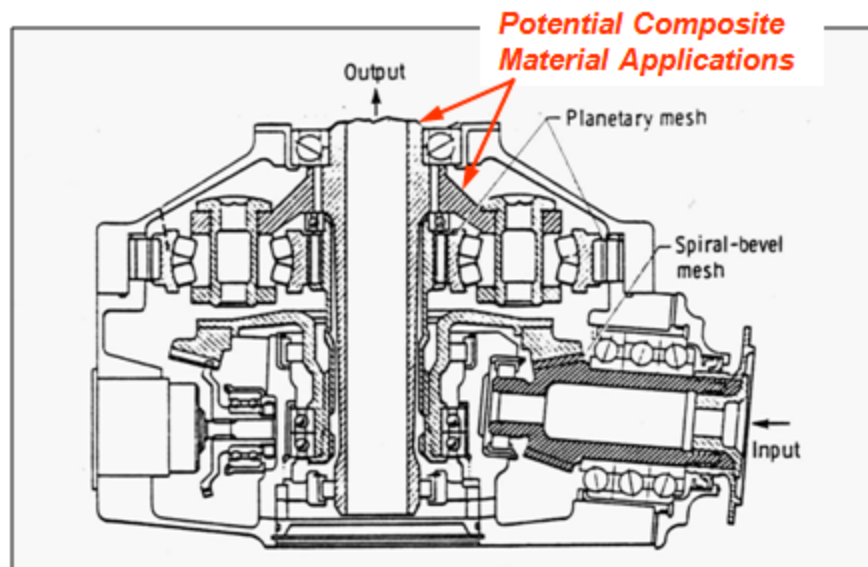
Figure 6.—OH-58 Main Transmission Cross-Section.

5.3   Configuration C—RITA Transmission

The National Rotorcraft Technology Center—Rotorcraft Industry Technology Association (NRTC/RITA) sponsored the design/development of a high-ratio, ultra-safe, high contact ratio, staggered and intermeshed planet, double-helical compound epicyclic gear system in order to improve capacity, improve safety, and reduce noise as compared to conventional simple planetary helicopter drives. The "RITA" Transmission was designed as a replacement for the CH-47D dual-stage simple planetary system (See Section 5.1). Objectives of the transmission development program were to design and test a CH-47D replacement planetary systems that reduced subsystem weight by 25 percent and reduced transmitted noise levels by 10 dB as compared to the CH-47D baseline.

Figure 7.—High-Ratio, Ultra-Safe, High Contact Ratio, Staggered and Intermeshed Planet, Double-Helical Compound Eplicyclic Transmission

The development program focused on a replacement for the simple planetary system, but also included a matching bevel gear mesh to keep the input speed of the developmental transmission similar to that of the CH-47D. The Input Pinion meshes with a Bevel Gear and transmits power into the Sun Gear. The Sun Gear Meshes with two sets of overlapping Compound Planetary Gears. Power is directed from the Sun Gear/Planet Gear Mesh up through the Compound Planet Gear Shafts and into a Double-Helical Mesh including the Compound Planet Gears and the Fixed Ring Gear. The Planet Gears are supported in a Planet Carrier. Then Planet Carrier is interconnected to the Rotor Shaft (Ref. 16).

- Power/Speed Data:
  - Input Power: 5,000 hp (Demo at 750 hp)
  - Input Shaft Speed: 3,938 rpm
  - Output Shaft(s) Speed: 225 rpm
- Power-Speed Index = 16.5
- Components Included in Parametric Weight Estimate:
  - Bevel Gear Mesh
  - Planetary Set
  - Rotor Shaft
- Assumptions:
  - Straddle mounted bevel pinion and gear
  - Magnesium housings
- Potential Composite Material Applications:
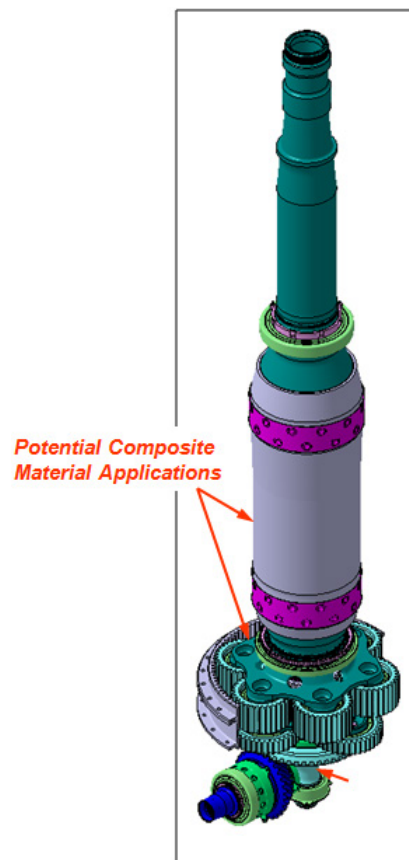 - Rotor Shaft
  - Planet Carrier
  - Planet Gears

5.4   Configuration D—Compound Planetary Differential Drive

The Compound Planetary Differential Drive (CPDD) is a continuation of the RITA Transmission (see Section 5.3). Originally designed for use in the SB>1 Defiant, Joint Multi-Role (JMR) Technology Demonstration Aircraft, the Compound Planetary Differential Drive (CPDD) receives a single mechanical input and generate two (2) equal, but opposite mechanical outputs. Potential applications include rotorcraft platforms with co-axial rotor systems and fixed wing platforms with coaxially rotating propeller shafts. Special materials under consideration include Aluminum Metal Matrix Composite for the Planet Carrier.

A series of compound planet gears mesh with the input gear (a large diameter external ring gear) and with a fixed, internal ring gear. The compound planet gears transmit mechanical power from the input gear into two (2) output gear meshes. Each compound planet gear has three (3) sets of gear teeth, all integral to the compound planet gear shaft. The 1st gear tooth set meshes with the aforementioned input gear and fixed ring gear. Mechanical power is then transferred through the compound planet gear shafts into two (2) discrete output gears. Each output gear spins in opposite directions, based on typical compound planetary gear ratios. Each discrete output gear is connected to an output shaft and spin at an equal frequency, but in opposite directions, creating a coaxial output that may be used for coaxial helicopter configurations (Ref. 17).

- Power/Speed Data:
  - Input Power: 5,720 hp
  - Input Shaft Speed: 2,419 rpm
  - Output Shaft(s) Speed: 212 rpm
- Power-Speed Index = 16.8
- Components Included in Parametric Weight Estimate:
  - Input Sun Gear
  - Compound Planetary Set
  - Output Gears
- Assumptions:
  - Straddle mounted gears
  - Magnesium housings
- Potential Composite Material Applications:
  - Planet Carrier
  - Output Shafts
  - Planet Gear Shafts
    (not shown)

Potential Composite Material Applications

Carrier 900 rpm

Input Sun Gear 2,419 rpm

Output Inner Shaft Ring Gear -212 rpm

Output Outer Shaft Ring Gear 212 rpm

Fixed Ring Gear 0 rpm

Planets 12x
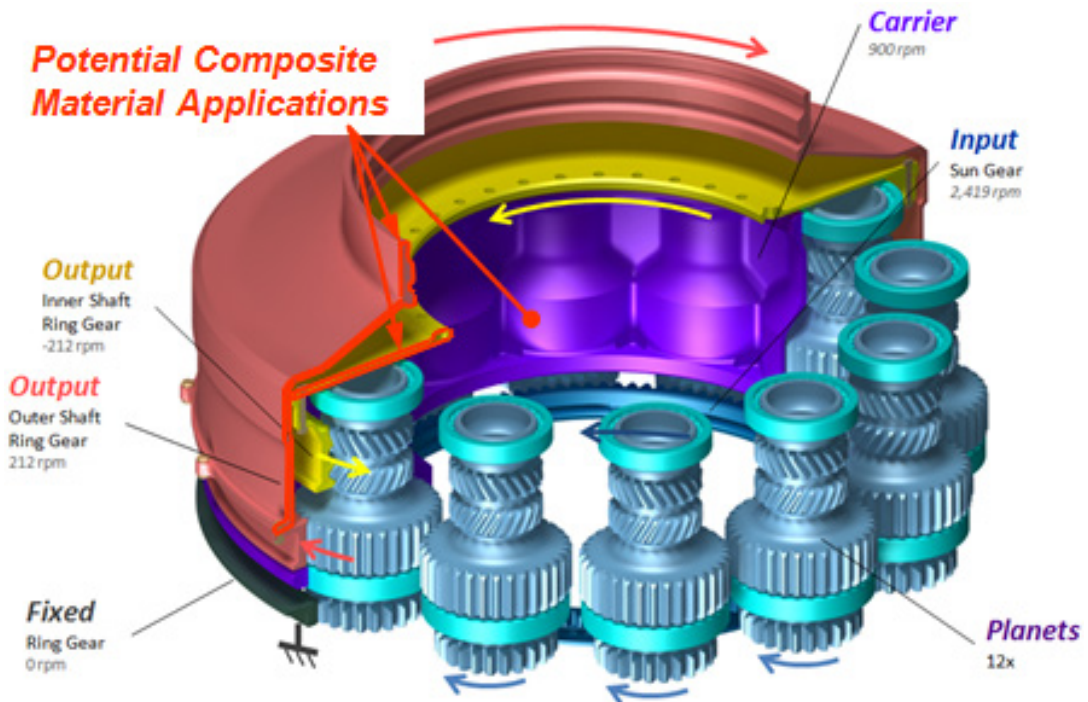
Figure 8.—Compound Planetary Differential Drive Transmission Configuration.

5.5   Configuration E—SABP Transmission

NASA contracted the development of a novel transmission configuration to reduce propulsion system weight and to reduce noise and vibrations. A high contact ratio epicyclic system was developed, called the Self-Aligning Bearingless Planetary (SABP) system. A 450 hp version of the SABP was designed and tested at speed, but without torque. Potential capacity increases exist to bring the power throughput up to 550 hp or more.

The Input Spur Gear Mesh transmits power to the Input Bevel Pinion. The Input Bevel Pinion/Gear Mesh transmits power into the Sun Gear. The Sun Gear Meshes with a Compound Planetary Gear Mesh. Power is directed from the Sun Gear/Planet Gear Mesh up through the Compound Planet Gear Shafts and into a Fixed Ring Gear and then into a 3rd parallel axis mesh which transmits power from the Compound Planet Gears to a Female Output Gear. The Output Gear is splined into the Rotor Shaft (Ref. 18).

- Power/Speed Data:
  - Input Power: 450 hp
  - Input Shaft Speed: 33350 rpm
  - Output Shaft(s) Speed: 348 rpm
- Power-Speed Index = 2.2
- Components Included in Parametric Weight Estimate:
  - Bevel Gear Mesh
  - Planetary Set
  - Rotor Shaft
- Assumptions:
  - Straddle mounted gears
  - Magnesium housings
- Potential Composite Material Applications:
  - Output Shaft and Web
  - Input Carrier (Shaft)
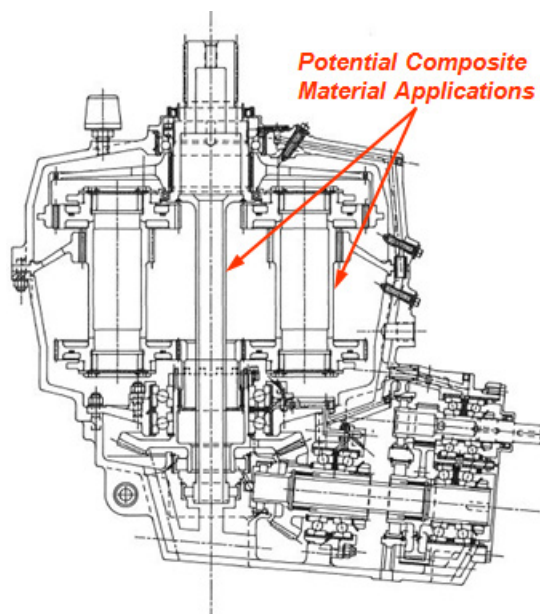
Figure 9.—85G1-1 High Contact Ratio Helicopter
Transmission Cross-Sectional View.

5.6 Configuration F—Proprietary Transmission Configuration

Power-Speed Index = 19.1

5.7 Configuration G—PSU Pericycler

Recent research activities have developed conceptual layouts for pericyclic transmission. Design intent was to create a high power-density transmission configuration with low parts count and high contact ratio.

An input carrier (shaft) creates wobbling motion of Pericyclic Motion Converter (PMC) Gears which mesh with Reaction Control Member (RCM) Gear and Output Gear. A pericyclic transmission is analogous to a coin wobbling on a table; a point on the edge of the coin travels the full circumference of the coin in one revolution, but traces a smaller circle when projected onto the table's surface in one revolution. The difference in diameters from the coin's circumference to the traced circle is the principle begine the pericyclic gear reduction (Ref. 13).

- Power/Speed Data:
  - Input Power: 5,000 hp
  - Input Shaft Speed: 3,927 rpm
  - Output Shaft(s) Speed: 225 rpm
- Power-Speed Index = 16.0
- Components Included in Parametric Weight Estimate:
  - Input Gear
  - PMC Gear
  - RMC Gear
  - Output Shaft
- Assumptions:
  - Straddle mounted gears
  - Magnesium housings
- Potential Composite Material Applications:
 - Output Shaft and Web
  - Input Carrier (Shaft)
  - Input Carrier (Shaft)
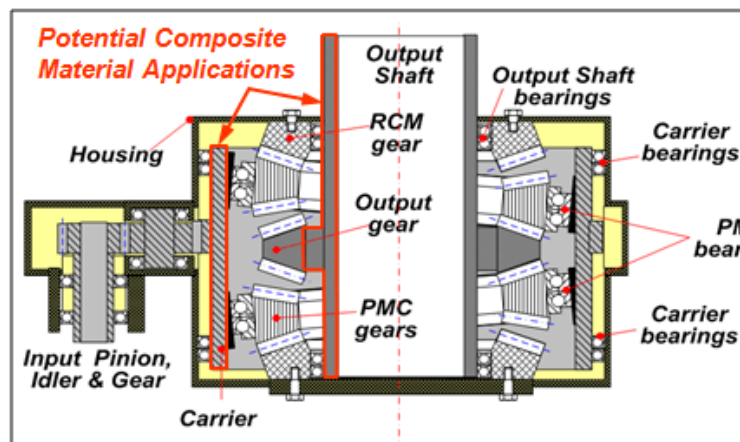
Figure 10.—Pennsylvania State University Pericycler Transmission Concept.

5.8   Configuration H—LCTR2 Prop-Rotor Transmission

The Large Civil Tilt Rotor (LCTR2) was a conceptual air vehicle developed to explore the benefits and possibilities of large tilt rotors for commercial applications (Ref. 3). The LCTR2 had two (2) 65 ft diameter rotors near the wing tips with a 107,700 lb gross weight and 19,800 lb payload for passengers and baggage. In order to accommodate the two (2) rotors located near the wing tips, two (2) rotor transmissions of similar configurations are located adjacent to each rotor. Conceptual engine and drive system configurations were developed in order to assess the benefits of reducing rotor tip speed in forward flight.

The Input Shaft connects through a series of Parallel Axis Gears into the Bull Gear. The Bull Gear is interconnected to the 1st Stage Simple Planetary System, which is then connected to a 2nd Stage Simple Planetary System. The 2nd Stage Simple Planetary System is connected to the Rotor Shaft. Cross shafts are connected to spiral bevel gears and then the Bull Gear, but shafting and associated gearing are not considered in this study (Ref. 3).

- Power/Speed Data:
  - Input Power: 8,125 hp
  - Input Shaft Speed: 15,000 rpm
  - Output Shaft(s) Speed: 191 rpm
- Power-Speed Index = 30.5
- Components Included in Parametric Weight Estimate:
  - Parallel Axis Input Gears
  - Bull Gear Mesh
  - 1st Stage Planetary Set
  - 2nd Stage Planetary Set
  - Rotor Shaft
- Assumptions:
  - Straddle mounted gears
  - Magnesium housings
- Potential Composite Material Applications:
  - Prop-Rotor Shaft
  - Long Quill Shafts
  - Parallel Axis Idler Gear Shafts
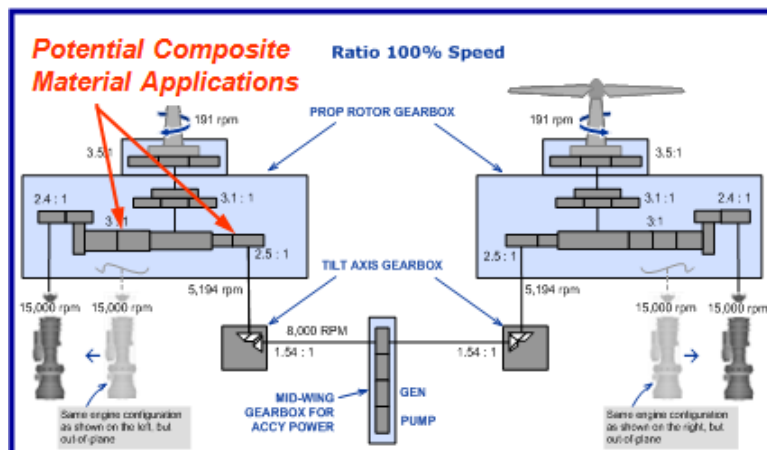
Figure 11.—Large Civil Tilt Rotor 2 Drive System Concept Schematic.

5.9   Configuration J—V-22 Prop-Rotor Transmission

The design of the V-22 began in 1982 to fit multi-mission requirements for the US Marine Corps, Special Operations Forces, and Navy. The V-22 was the first fielded, production aircraft to integrate efficient hover with high-speed cruise capabilities. The V-22 has two (2) 38 ft diameter rotors near the wing tips. In order to accommodate the two (2) rotors located near the wing tips, two (2) rotor transmissions of similar configurations are located at each rotor.

The Input Shaft connects through series of Parallel Axis Gears into the Bull Gear. The Bull Gear transmits power into the 1st Stage Sun Gear which meshes with a series of Planetary Gears. The Planetary Gears mesh with a Fixed Ring Gear and are interconnected to the 1st Stage Planet Carrier. The 1st Stage Planet Carrier transmits power into the 2nd Stage Sun Gear, which is similarly related to the 2nd Stage Planet Gears, 2nd Stage Fixed Ring Gear, and 2nd Stage Planet Carrier. The 2nd Stage Planet Carrier is interconnected to the Prop-Rotor Shaft (Ref. 19).

- Power/Speed Data:
  - Input Power: 5,011 hp
  - Input Shaft Speed: 15,000 rpm
  - Output Shaft(s) Speed: 397 rpm
- Power-Speed Index = 11.0
- Components Included in Parametric Weight Estimate:
  - Parallel Axis Input Gears
  - Bull Gear Mesh
  - 1st Stage Planetary Set
  - 2nd Stage Planetary Set
  - Rotor Shaft
- Assumptions:
  - Straddle mounted gears
  - Magnesium housings
- Potential Composite Material Applications:
  - Prop-Rotor Shaft
  - Parallel Axis Idler Gears
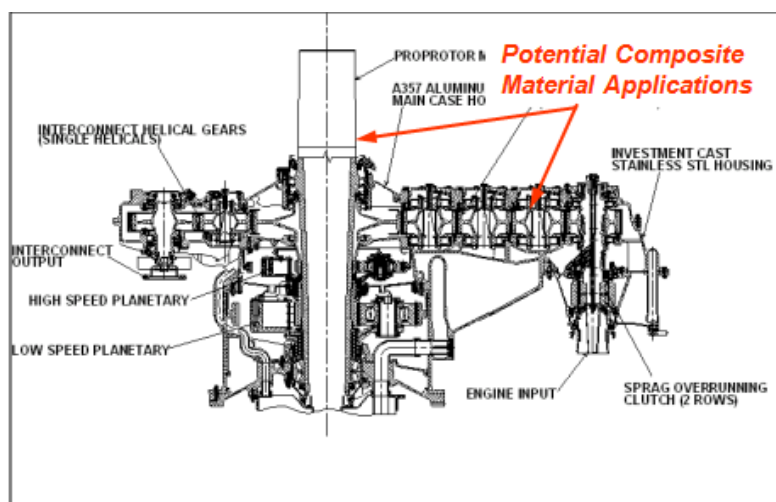
Figure 12.—V-22 Prop-Rotor Transmission Cross-Section.

5.10   Configuration K—Bell ART II

The Advanced Rotorcraft Transmission (ART) II program developed and demonstrated advanced mechanical power transmission technology for high-precision, rotorcraft transmissions. The programs objective were to increase shaft horsepower-to-weight ratio by 25 percent, reduce drive train generated noise by 10 dB, increase reliability by a factor of two (2), and reduce acquisition costs by 10 percent. The Bell ART II Transmission was designed as a replacement for the V-22 Prop-Rotor Transmission.

The Input Shaft connects through high speed double helical meshes into two (2) torque splitting Double Helical Gears. Power is transferred from the Double Helical Gears, through torsionally compliant Quill Shafts, and into double helical Bull Pinions. The Bull Pinions mesh the same Bull Gear, which is integral to the Sun Gear. The Sun Gear meshes with Planetary Gears which mesh with a Fixed Ring Gear and the carrier of the planetary system is connected to the Prop-Rotor Shaft (Ref. 2).

- Power/Speed Data:
  - Input Power: 5,011 hp
  - Input Shaft Speed: 15,000 rpm
  - Output Shaft(s) Speed: 397 rpm
- Power-Speed Index = 11.0
- Components Included in Parametric Weight Estimate:
  - Parallel Axis Input Gears
  - Bull Gear Mesh
  - Planetary Set
  - Prop-Rotor Shaft
- Assumptions:
  - Straddle mounted gears
  - Magnesium housings
- Potential Composite Material Applications:
  - Prop-Rotor Shaft
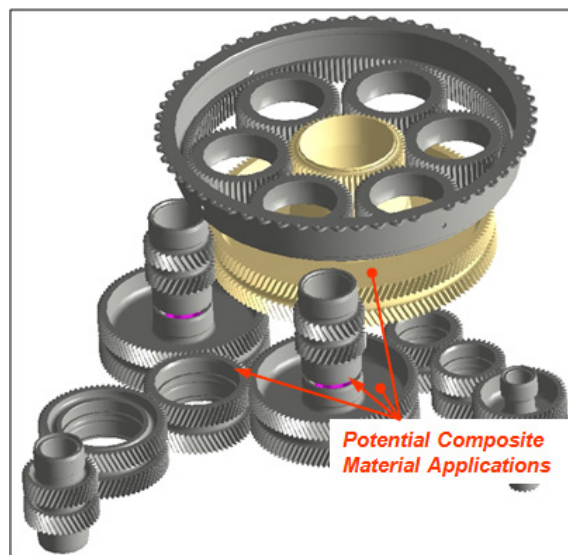 - Quill Shafts
  - Parallel Axis Idler Gears

Figure 13.—Bell Advanced Rotorcraft Transmission (ART) II Prop-Rotor Transmission Configuration.

5.11 Configuration L—Bull Gear Block Diagram

Initial concepts for hybrid composite dynamic components led to an understanding that composites are best implemented in transmissions that incorporate large uninterrupted surfaces. Large diameter Bull gears and long shafts were considered to be good examples of transmission components with large, uninterrupted surfaces. A block diagram was developed to begin conceptualizing a transmission that incorporates a bull gear with a large plan form and a long rotor shaft. Such a configuration could be a replacement for tandem rotor configurations, like the CH-47 Chinook Aft Transmission or could be utilized for conventional helicopters, as seen in the CH-53K King Stallion.

For an initial configuration, the Configuration L Bull Gear Block Diagram was developed as a replacement for the CH-47 Chinook Aft Transmission; however, this concept could be adapted to conventional helicopters by adding another bevel stage to the input or adding a 2nd or 3rd input. See Configuration R CH-53K Main Transmission for a bull gear example with three (3) inputs.

The conceptualized configuration sends power into a single input shaft into a bevel mesh which turns power roughly 90° (86° in the case of the CH-47 Aft Transmission). Two (2) integral spur gear meshes split the torque path into four (4) bull pinions that drive the bull gear. An integral Aft Rotor Shaft is mechanically connected to the bull gear through a spline joint and set of preloaded bearings. The rotor shaft is approximately eight (8) ft long to extend from inside the transmission to the top of the CH-47 Aft Pylon. A similar integral aft rotor shaft configuration was utilized on the Boeing 360 Technology Demonstrator. Note, accessory power take-offs were omitted for this study, but may be added in future design studies.

For this study, three (3) different input powers were included for their impact on the parametric weight estimates. 3,000, 5,000, and 7,000 hp were selected in order to span a larger cross section of potential helicopter classes. Additionally, housings were assumed to be made of magnesium, as is typical for Army helicopters; the input pinion, bevel gear, and bull gear were assumed to be straddle mounted; and the bull pinion is assumed to be cantilevered at the bull gear mesh. The parametric weight study included a single bevel mesh, four (4) spur gear meshes, four (4) helical gear meshes all meshing with a single bull gear, and an eight (8) ft long rotor shaft. Note, accessory power take-off gear sets were omitted for this study, but may be added in future design studies.

- Power/Speed Data:
  - Input Power: 3,000, 5,000, and 7,000 hp
  - Input Shaft Speed: 7,000 rpm
  - Output Shaft(s) Speed: 225 rpm
- Power-Speed Index = 11.2, 16.5, and 21.3 (respectively)
- Components Included in Parametric Weight Estimate:
  - Input Bevel Gear Mesh
  - Parallel Axis Split Torque Gear Meshes
  - Bull Gear Mesh
  - Rotor Shaft
- Assumptions:
  - Straddle mounted gears
  - Magnesium housings
- Potential Composite Material Applications:
  - Gear Webs
  - Quill Shafts
  - Rotor Shaft
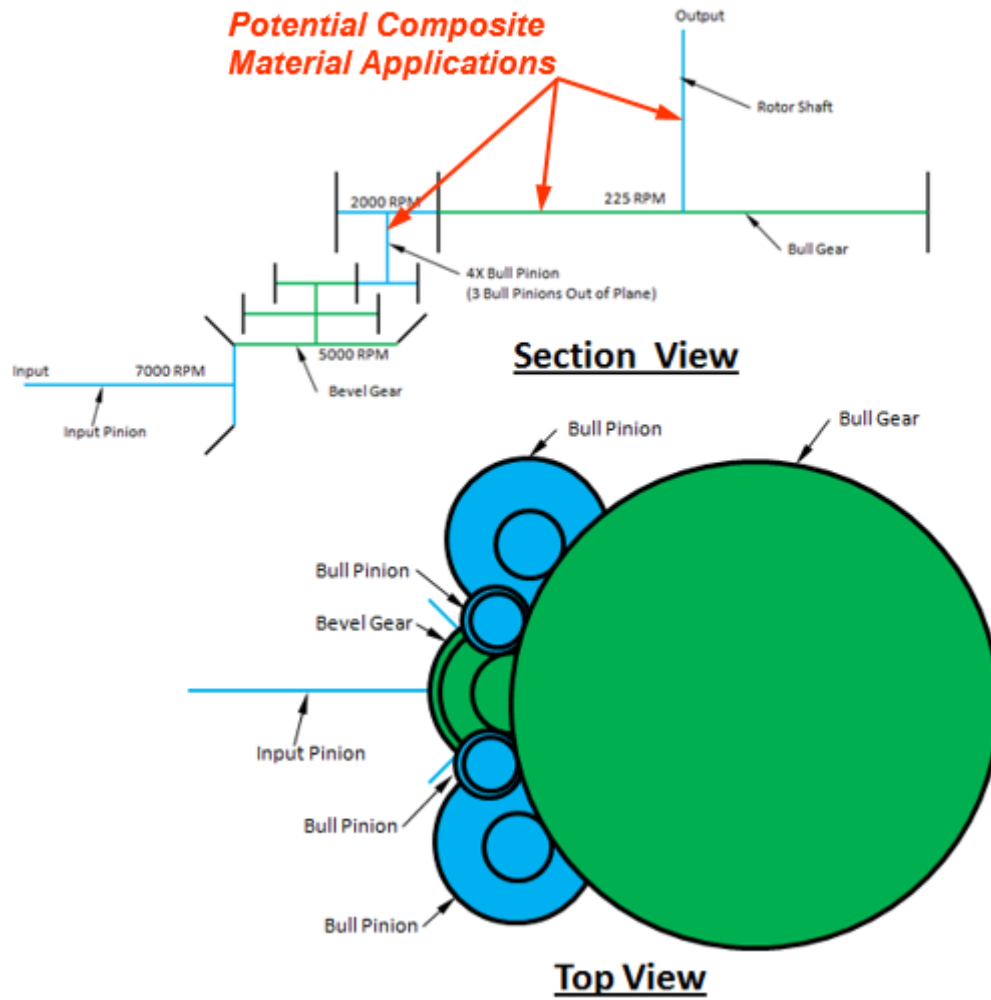
Figure 14.—Concept Diagram of Split-Torque Bull Gear for Helicopter Applications.

5.12   Configuration M—AH-64 Apache Main Transmission

The AH-64 Apache Helicopter was designed in the early 1970's with first flight occurring c. 1975. Recently, the AH-64 Apache Main Transmission was redesigned for the Block II Program, incorporating advanced split torque face gears, in place of the incumbent spiral bevel input gear stage, among other changes. Because of the novel Block II transmission configuration, the Block I transmission configuration was utilized for this study.

Two (2) individual Input Bevel Gear Meshes direct power into two (2) Helical Pinions. The two (2) Helical Pinions mesh with a common Bull Gear which sends power to an integral Sun Gear. The Sun Gear meshes with Simple Planetary Gears which mesh with a Fixed Ring Gear and are interconnected to the Planet Carrier. The Vertical Drive Shaft is splined into the Planet Carrier and transmits torque to the Rotor Head (Ref. 20).

- Power/Speed Data:
  - Input Power: 3,400 hp
  - Input Shaft Speed: 5,750 rpm
  - Output Shaft(s) Speed: 258 rpm
- Power-Speed Index = 9.0
- Components Included in Parametric Weight Estimate:
  - Input Bevel Gear Mesh
  - Bull Gear Mesh
  - Planet System
  - Vertical Drive Shaft
- Assumptions:
  - Straddle mounted gears
  - Magnesium housings
- Potential Composite Material Applications:
  - Gear Webs
  - Gear Shafts
  - Planet Carrier
  - Drive Shaft
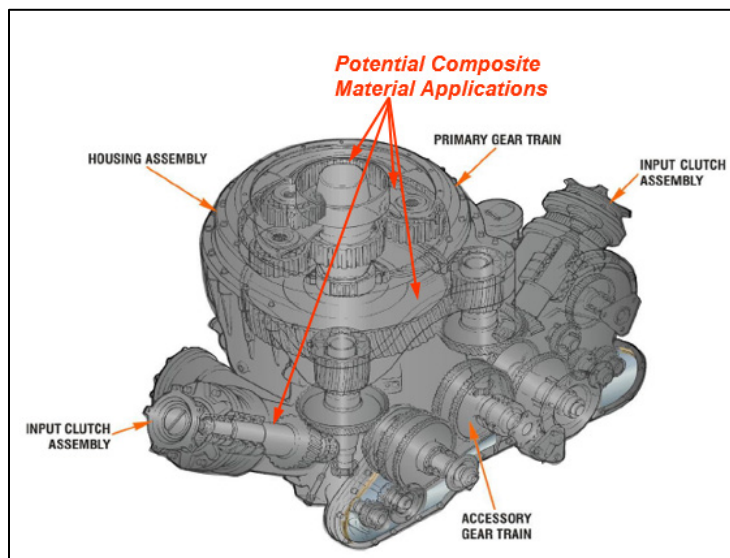
Figure 15.—AH-64 Main Transmission Configuration.

5.13   Configuration N—RAH-66 Main Transmission

The RAH-66 Comanche was a helicopter designed for the reconnaissance and attack mission. Stealth technology was a primary consideration for the RAH-66, as well as the ducted fan tail, which provided exceptional lateral control of the aircraft.

The RAH-66 Main Transmission consists of two (2) Input Pinions which mesh with one (1) Bevel Gear, each. Each Bevel Gear directs power to a Spur Pinion, which splits the torque path to two (2) Spur Gears, each, totaling four (4) SpurGears in the second reduction stage. The Spur Gears direct power to Double Helical Bull Pinions, which mesh with a single Bull Gear. The Bull Gear is interconnected to the Rotor Shaft (Ref. 21).

- Power/Speed Data:
  - Input Power: 2,400 hp
  - Input Shaft Speed: 23,000 rpm
  - Output Shaft(s) Speed: 355 rpm
- Power-Speed Index = 7.3
- Components Included in Parametric Weight Estimate:
  - Input Bevel Gear Mesh
  - Split Torque Meshes
  - Bull Gear Mesh
  - Rotor Shaft
- Assumptions:
  - Straddle mounted gears
  - Magnesium housings
- Potential Composite Material Applications:
  - Torque Split Quill Shafts
  - Gear Webs
  - Rotor Shaft
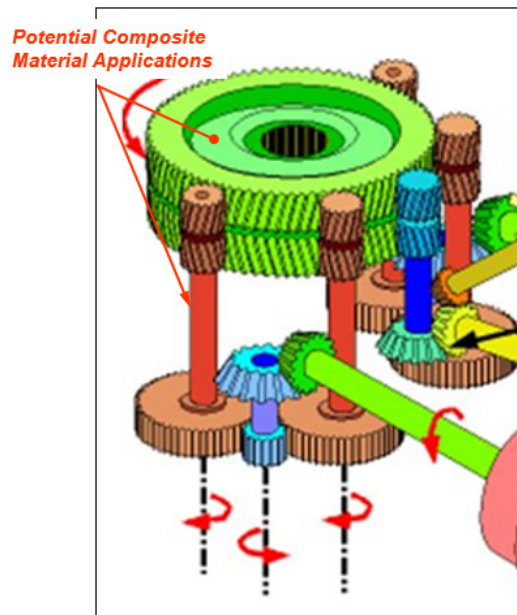
Figure 16.—RAH-66 Main Transmission Configuration.

5.14 Configuration P—UH-60 Main Transmission

The UH-60 is a utility helicopter within the U.S. Army fleet and around the world for defense and humanitarian applications.

Two Input Bevel Pinions combine at single Bull Gear. The Bull Gear is mechanically fastened to the Sun Gear which meshes with 5 Planets interconnected to a Planet Carrier splined into the Rotor Shaft (Ref. 22).

- Power/Speed Data:
  - Input Power: 3.400 hp
  - Input Shaft Speed: 5,750 rpm
  - Output Shaft(s) Speed: 258 rpm
- Power-Speed Index = 10.6
- Components Included in Parametric Weight Estimate:
  - Bevel Gear Meshes
  - Bull Gear
  - Planetary System
  - Rotor Shaft
- Assumptions:
  - Straddle mounted gears
  - Magnesium housings
- Potential Composite Material Applications:
  - Output Shaft
  - Bull Gear Web
 - Planet Carrier (Not Shown)
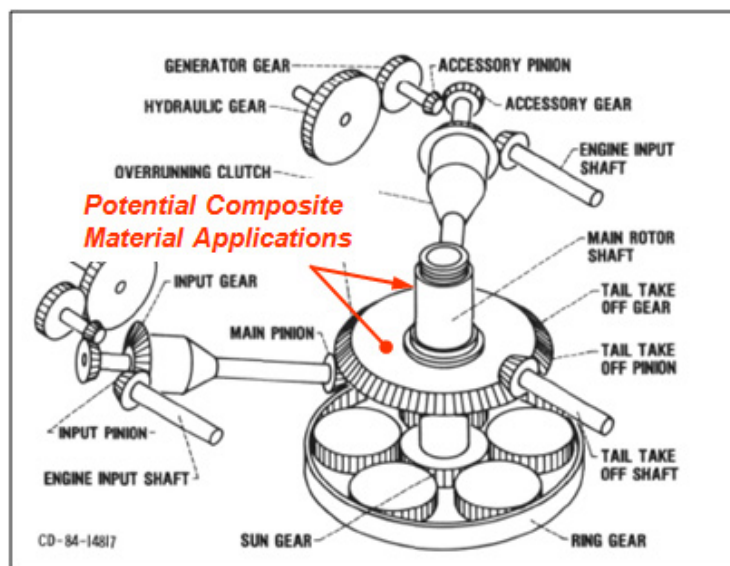
Figure 17.—UH-60 Main Transmission Configuration.

5.15   Configuration R—CH-53K Main Transmission

The CH-53K is a redesigned version of the CH-53E. The CH-53K was designed to sling load 27,000 lb at 3,000 ft above sea level at 91.5 °F. The Main Gearbox is a split torque, bull gear configuration that was selected after design trade studies showed that a planetary system, similar to the CH-53E Main Gearbox, would not transmit the required power within the given geometric envelope. The CH-53K is designed for ship-board operations, so aluminum housing are assumed for corrosion resistance.

Three individual Input Bevel Gear Meshes direct power into Spur Gear Meshes where power is split into four Spur Gears per Input Bevel Gear. Each Spur Gear is interconnected to Helical Input Pinion through Torsionally Compliant Quill Shafts. Twelve (12) Helical Input Pinions mesh with one (1) Bull Gear which is splined into the Rotor Shaft (Ref. 23).

- Power/Speed Data:
  - Input Power: 22,500 hp
  - Input Shaft Speed: 5,750 rpm
  - Output Shaft(s) Speed: 258 rpm
- Power-Speed Index = 70.2
- Components Included in Parametric Weight Estimate:
  - Bevel Gear Meshes
  - Spur and Helical Gear Meshes
  - Rotor Shaft
- Assumptions:
  - Straddle mounted gears
  - Aluminum housings
- Potential Composite Material Applications:
  - Rotor Shaft (Not Shown)
  - Bull Gear Web
  - Quill Shafts
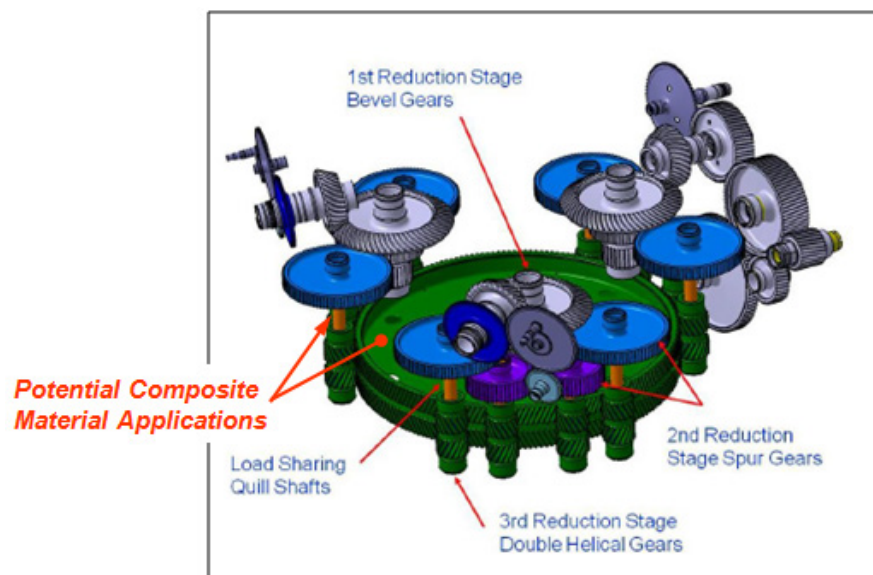
Figure 18.—CH-53K Main Transmission Configuration.

5.16　Configuration S—Mi-26 Main Transmission

The Mi-26 Halo is a product of the Mil Moscow Helicopter Plant and is the largest helicopter currently in-service (Ref. 24). The Mi-26 is a "heavy lift" helicopter used for civilian and defense applications.

Two (2) Input Shafts are mechanically attached to two Bevel Pinions per Input Shaft. Each Bevel Pinion meshes with a corresponding Bevel Gear which transmits power through Quill Shafts to two Compound Parallel Axis Gears. The Compound Parallel Axis Gears mesh with a Torque Splitting Bull Gear which in connected to the Rotor Shaft (Ref. 25).

- Power/Speed Data:
  - Input Power: 19,725 hp
  - Input Shaft Speed: 8,300 rpm
  - Output Shaft(s) Speed: 132 rpm
- Power-Speed Index = 77.0
- Components Included in Parametric Weight Estimate:
  - Input Bevel Gear Mesh
  - Bull Gear Mesh
  - Rotor Shaft
- Assumptions:
  - Straddle mounted gears
  - Magnesium housings
- Potential Composite Material Applications:
  - Gear Webs
  - Gear Shafts
  - Planet Carrier
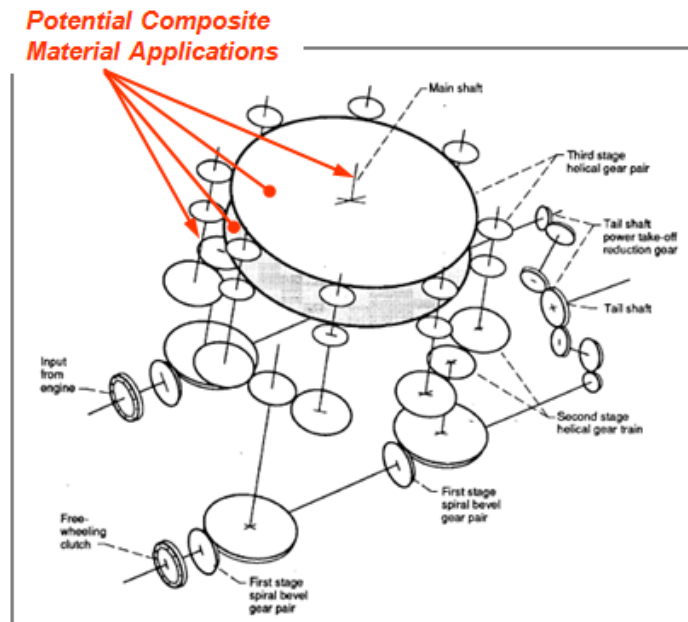 - Drive Shaft

Figure 19.—Mi-26 Main Transmission Concept Diagram.

6.0 Component Designs and Trade Studies

Design and analysis work was performed on select rotating dynamic components in order to develop a Special Features Factor for rotating dynamic components with extensive use of composite materials. Weights data for hybrid composite gear designs and rotor shaft designs from AH-64 and CH-47 applications (Refs. 29 and 4) were included in the study, where applicable, to build confidence in the conceptual design and develop a more comprehensive data package to feed the Special Features Factor (see Section 6.5). The conceptual design and analysis work performed in this project developed layouts and configurations to assess critical design features, such as strength or stiffness. The designs provided herein are not recommendations for any individual configuration, but are intended to support the development of the Special Features Factors and provide guidance for technical recommendations and follow-on research.

Gear shafts, rotor shafts, gear webs, etc. have a variety of challenges associated with integration of composite shaft or web sections. Principal among these challenges is the incorporation and integration of features such as spline teeth, mechanical screw threads, or functional equivalents; therefore, a lower risk method to introduce composite materials into the transmission system is to introduce composite materials into areas with large, uninterrupted sections of surfaces without mechanical interfaces. This obviously led to composite applications for long shaft sections and bull gear webs.

To progress from baseline parametric weight estimates into hybrid transmission parametric weight estimates it was important to baseline representative dynamic components to create a basis of estimation for weight savings benefits. The following sections outline the design details and analysis methods used to provide preliminary sizing on a select group of components. The predicted weight of these components were then extrapolated to include gears and shafts throughout each transmission configuration, through the use of a Special Features Factor (see Section 7.0). The final hybrid transmission parametric weight estimates assumes the extensive uses of composites or advanced materials through each gear and shaft system as applicable.

The Configuration "L" Block Diagram Transmission was used to size Rotor Shafts and Bull Gears for this study. The Rotor Shaft was arbitrarily selected to be similar in length to the CH-47 Chinook Aft Rotor Shaft. The Bull Gear was arbitrarily selected to be similar in size to the CH-47 Stationary Ring Gear.

6.1 Rotor Shafts

Preliminary sizing and conceptual layouts of two (2) rotor shaft configurations for the Configuration "L" Block Diagram have been evaluated. The baseline rotor shaft configuration is shown in Figure 20. It is a one-piece Ti-6Al-4V titanium alloy shaft with integral splines, bearing interfaces, and mechanical screw threads that connect the bull gear to the lower end of the rotor shaft and similar interfaces to connect the upper end of the rotor shaft to the conceptual rotor head.

The 1st hybrid composite rotor shaft configuration developed under this effort replaces the baseline, one-piece titanium shaft with a three-piece titanium and carbon fiber-reinforced epoxy matrix shaft, as shown in Figure 20. Two (2) titanium end fittings are interconnected by bolted joints to a fiber-reinforced epoxy matrix shaft in the shaft section connecting the two splined, preloaded areas. The titanium end fittings will provide necessary mechanical interfaces, such as splines, to transmit power from the main transmission to the rotor head. The three-piece rotor shaft configuration is estimated to decrease the weight of the Rotor Shaft by 13 percent when compared to the incumbent design.

The 2nd rotor shaft configuration replaces the baseline, one-piece titanium shaft with a two-piece titanium and fiber-reinforced epoxy matrix shaft, see Figure 20. One (1) titanium end fitting is co-cured or co-bonded to a fiber-reinforced epoxy matrix shaft. The titanium end fitting is splined into the main rotor gear box and contains the applicable bearing and locknut interfaces. The Rotor Shaft to Rotor Head interface eliminates one (1) of the titanium end fittings and extends the composite structure up through the Rotor Head. The spline interface between the Rotor Head and Rotor Shaft is replaced with a cone seat joint where torque is assumed to be transmitted through frictional interfaces between the cone surfaces and hub under immense axial preload inherent to this type of joint. If this configuration is further developed or matured, the absence of positive engagement features for transmitting torque (i.e., splines) should be a consideration. While the frictional capacity of this type of joint is tremendous and is predicted to far exceed torque capacity requirements, it is recommended that failsafe design provisions be evaluated such as a secondary positive engagement feature or mechanism to monitor shaft strain or preload while in operation. The two-piece Rotor Shaft configuration is estimated to decrease the weight of the Rotor Shaft by 34 percent when compared to the incumbent design.
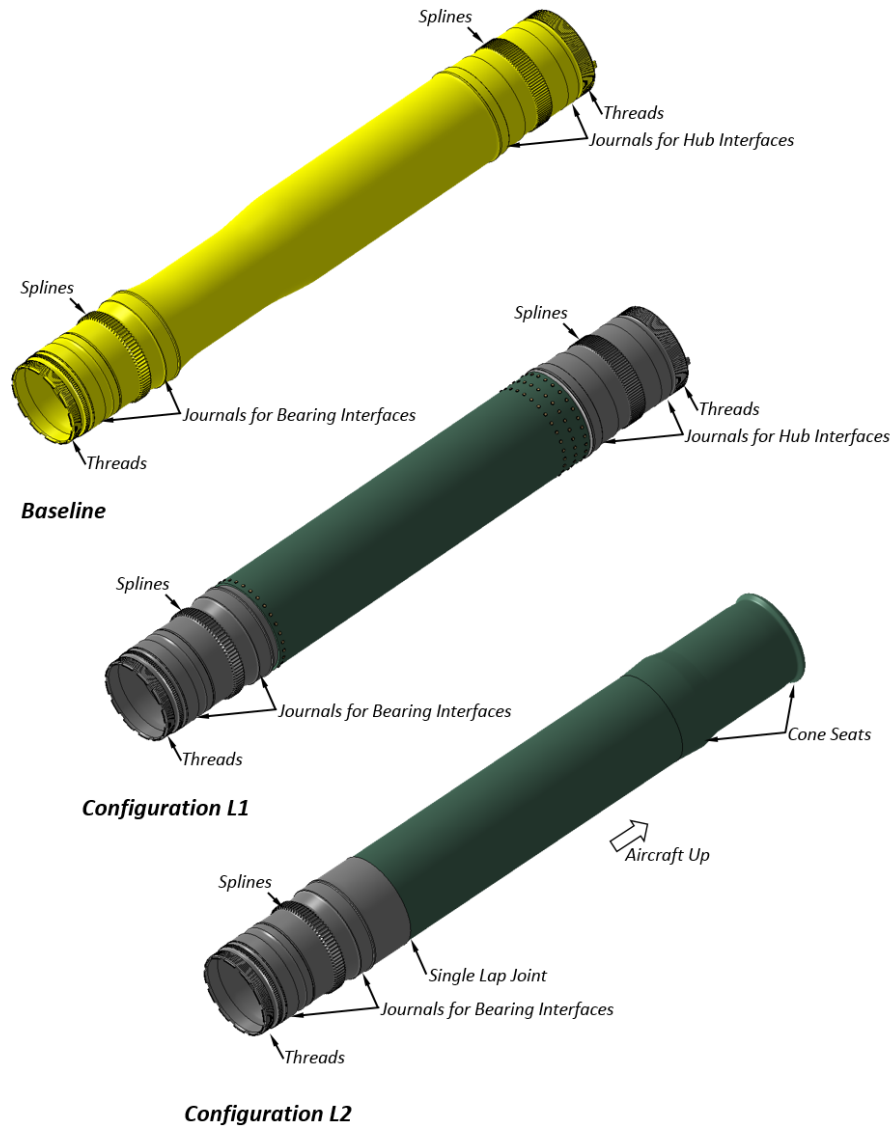
Figure 20.—Configuration "L" Rotor Shafts Studied.

TABLE 3.—WEIGHTS TABLE FOR BASELINE AND CONFIGURATION "L" ROTOR SHAFTS

Component description	Quantity			Unit weight, lb		
	Baseline	L1	L2	Baseline	L1	L2
Upper shaft section	1	1	1	256	101	106
Center shaft section	-	1	-	----	54	-----
Lower shaft section	-	1	1	-----	62	62
Fasteners	-	120	-	-----	0.04	-----
Calculated assembly weight, lb				256	222	168
Calculated weight delta, lb				-----	−34	−88

Table 3 provides the detailed weight estimates for each rotor shaft configuration. The quantity of each component contained within each rotor shaft assembly is provided, along with corresponding unit weights for each component. The calculated assembly weight includes the summation of component quantity multiplied by its corresponding unit weight, see Equation (21). The calculated weight delta is the difference between the Baseline Configuration Weight and the applicable composite hybrid configuration weight.

$$\text{Calculated Assembly Weight} = \Sigma \left(\text{Quantity} \right) \left(\text{Unit Weight} \right) \qquad (21)$$

Strength (stress and strain) analysis was performed to estimate the strength of each component in order to substantiate the weights claimed in Table 3. For this study margins of safety of –0.05 or greater were deemed acceptable for initial weight estimates due to uncertainty in the design and evaluation of the design. Negative margins and critical sections are typically reassessed as configurations mature and more detailed design and analysis data becomes available. Specifically, negative margins are deemed acceptable because the average weight savings was used to calculate the hybrid composite parametric weight estimates for each configuration, thereby reducing the sensitivity to weight savings of any single configuration.

An ultimate strength load case was used for initial rotor shaft sizing. The 1st composite shaft configuration (3 piece, bolted joint) was initially sized using IM7 graphite tape with a HexPly 8552® (8552) epoxy matrix. This material system is widely used throughout aerospace applications and similar IM7/8552 material form was previously selected for the H-47 Composite Rotor Shaft (Ref. 4) making it a good candidate material to begin weights trades.

After initial sizing, the preloaded, mechanical fasteners were analyzed for bearing strength. As stated previously, sizing began with three (3) rows of 30 fasteners at the upper bolted joint interface and one (1) row of 30 fasteners at the lower bolted joint interface. Initial sizing assumed 0.2500 in. diameter fasteners in all four rows, but further analysis showed that the fastener diameter should be increased to 0.3125 in. Weight estimates in Table 3 represent the configuration with 0.3125 in. diameter fasteners.

The 2nd Rotor Shaft Configuration used a similar IM7/8552 towpreg material system, form, and layup as the H-47 Composite Rotor Shaft (Ref. 4). After initial sizing, the cone seats at the upper end of the shaft (including the associated Locknut, see Section 10.2.1) and the bonded joint at the lower end of the shaft were analyzed to substantiate weight estimates. Axisymmetric locknut design guidance from Birger (Ref. 26) was used to analyze the locknut associated with the Configuration L2 Upper Cone Seat. The composite cone seats were analyzed by equating the applied preload and applied bending moment in the hub stackup to an external pressure on a thick-walled cylinder. Hoop stresses were then calculated in accordance with guidance from Roark (Ref. 27) and compared against allowables of the parent composite material. Margins of safety for the bonded lap joint of Configuration L2 were written against the strength

TABLE 4.—ROTOR SHAFT INITIAL ANALYSIS MINIMUM MARGINS OF SAFETY

Configuration	Minimum margin of safety	Critical section
Baseline	0.04	Shaft body
Configuration L1	0.02	Lower bolted joint (Fasteners)
Configuration L2	[a]–0.01	Upper cone seat (Ply compression)

[a]Acceptable for parametric weight trade studies only. Future work requires modification to design to generate positive margins of safety.

of the bonded lap joint as compared to the general strength of the bonded metallic section following guidance from Niu (Ref. 28). Minimum margins of safety are shown in Table 4 based on initial sizing and corresponding stress analysis.

6.2 Bull Gears

Preliminary sizing and conceptual layouts of three (3) bull gear configurations for the Configuration "L" Block Diagram have been evaluated. The baseline bull gear configuration is shown in Figure 21. The Configuration "L" Bull Gear is mechanically interconnected to the rotor shaft, see Section 6.1 for rotor shaft description. The bull gear is designed to transmit applied torque, radial loads, axial loads, and bending moments. Applied torque is transmitted from the Bull Gear Teeth, into the Bull Gear Teeth's backup structure (Gear Rim), into the Gear Web and into the Bull Gear's Female Spline, which interfaces with the rotor shaft's lower male spline. Applied radial and axial loads and bending moments are transmitted in a similar fashion beginning at the Bull Gear's Teeth and Rim and traveling through the Gear Web, except the load path is then transmitted into an integral Shaft Section. The Shaft Section reacts radial loads through piloted bores that interface with corresponding journals on the mating Rotor Shaft. The Shaft Section reacts axial loads through a shoulder machined into the mating Rotor Shaft at one end, and through the compressed face of a Locknut at the opposite end of the Shaft Section. The Locknut is threaded into the mating Rotor Shaft and is also used to preload the Shaft Section. Bending moments are reacted through a combination of the pilots and shoulder/locknut features.

The 1st bull gear configuration (Configuration L1) that was developed replaced the incumbent, one-piece steel bull gear with a metallic and carbon fiber reinforced structure. The carbon fiber reinforced structure replaces the Gear Web and Shaft Section, see Figure 21. This configuration utilizes a sinusoidal lap joint similar to that of the composite hybrid bull gear developed by NASA and the Army Research Laboratories (ARL) (Ref. 1). The sinusoidal lap joint connects the gear web to the gear rim to transmit torque, axial loads, radial loads, and bending moments. The 1st composite hybrid bull gear configuration developed is estimated to decrease the weight by 24 percent over the incumbent design with a steel Gear Rim but does not include a method to mechanically transmit torque from the Bull Gear Web into the mating Rotor Shaft. Configuration L1 may include pin joint in lieu of a fixed spline, estimating the effects of adding a pin joint, similar to that on the CH-47 Chinook Aft Rotor Shaft, is expected to add a few pounds to the overall gearbox weight. Future work should consider weight differences between pin joints and fixed splines as well as assembly and installation considerations for each application.

The 2nd bull gear configuration (Configuration L2) developed replaces the incumbent, one-piece steel bull gear with a metallic and carbon fiber reinforced structure. This is similar to the first configuration, except the composite web is split into upper and lower webs with integral upper and lower shaft sections and a metallic spline array is assembled between each composite section. Each composite web is bonded to the gear rim and includes finer pitch splines and a pilot bore and shoulder. The bond line is assumed to transmit 100 percent of the gear loads with the fine pitch splines providing a fail-safe load path. The tight fitting pilot bore is intended to improve the positional accuracy of the gear rim to reduce "orbiting"

observed in composite hybrid gear testing at GRC (Ref. 1). The composite web then transitions into an integral composite hub. The composite hub is bonded to a metallic spline array with a fail-safe Curvic spline between the composite hub and metallic spline array, see Figure 21. The Gear Rim is made from P-53 Steel Alloy and the spline array is made from Ti-6Al-4V Titanium Alloy. The 2nd composite hybrid Inner Bull Gear configuration developed is estimated to decrease the weight by 23 percent over the incumbent design.
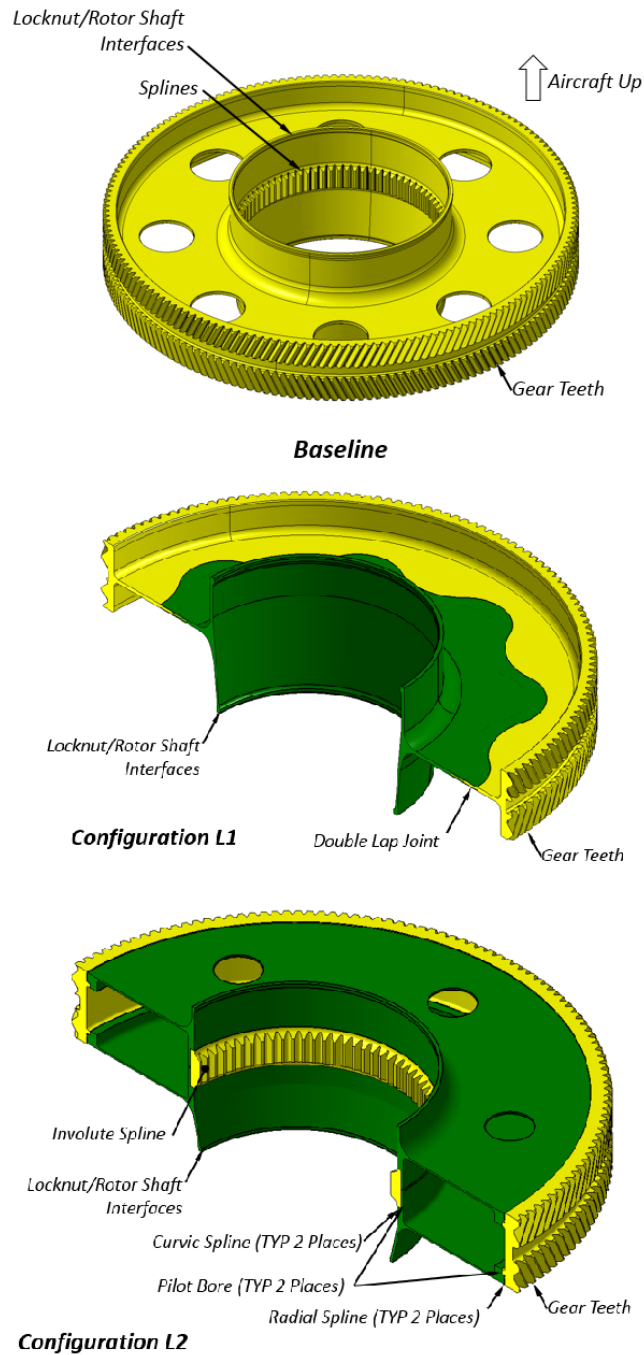

Figure 21.—Configuration "L" Bull Gears Studied.

A 3rd Bull Gear configuration was studied (Configuration L3) in order to demonstrate the impacts of introducing light materials into the gear rim and gear tooth. Material selection based on material index guidance (see Section 3.3) for specific strength and imposing the design constraint of high fracture toughness results in titanium as a reasonable candidate for gear teeth. Coated titanium splines are currently used in flight critical spline joints, but have lower wear resistance than typical gear steels, like case hardened 9310. Future advances in material processing or coating systems may develop a titanium alloy gear tooth surface that performs well in the contact stress problem within the involute profile. The 3rd bull gear configuration is similar to Configuration L2 (see Figure 21), except the steel gear rim is replaced with a Ti-6Al-4V Titanium Alloy gear rim. Configuration L3 was not considered during the special features factor development because titanium gear teeth have yet to demonstrate themselves in a controlled environment. This technology requires further development and evaluation to determine if this technology is viable for incorporation in rotorcraft transmissions.

Table 5 provides weights tables for each bull gear configuration. The quantity of each component contained within each bull gear assembly is provided, along with corresponding unit weights for each component. The calculated assembly weight includes the summation of component quantity multiplied by its corresponding unit weight, see Equation (21). The calculated weight delta is the difference between the Baseline Configuration Weight and the applicable composite hybrid configuration weight.

Similar to the Rotor Shaft analysis presented, strength (stress and strain) analysis was performed on the noted Bull Gear configurations to estimate the strength of each configuration with the intent to substantiate the weights claimed in Table 5. Again, margins of safety of –0.05 or greater were deemed acceptable for initial weight estimates due to uncertainty in the design and evaluation of the design. Negative margins and critical sections are typically reassessed as configurations mature and more detailed design and analysis data becomes available.

An ultimate strength load case was used for initial composite web sizing. The 1st composite web and hub configuration (integral composite web and hub) was initially sized using IM7/8552 towpreg, similar to the H-47 Composite Rotor Shaft (Ref. 4).

After initial sizing, the bonded joint interface that provides the connection between the metallic gear rim and the composite web was analyzed to substantiate weight and size estimates. The bond line was sized assuming that 100 percent of the gear forces will be transmitted through the bonded joint interface. This is a conservative assumption because in practice the sinusoidal pattern will provide a mechanical interlock adding a secondary, mechanical load path.

TABLE 5.—WEIGHTS TABLE FOR BASELINE AND CONFIGURATION "L" BULL GEARS

Component description	Quantity				Unit weight, lb			
	Baseline	L1	L2	L3	Baseline	L1	L2	L3
Gear rim	1	1	1	1	142	99	93	62
Integral web and hub	-	1	2	2	----	9	15	15
Spline array	-	-	1	1	----	----	8	8
Calculated assembly weight, lb					142	108	115	85
Calculated weight delta, lb					----	−34	−27	−57

TABLE 6.—BULL GEAR INITIAL ANALYSIS MINIMUM MARGINS OF SAFETY

Configuration	Minimum margin of safety	Critical section
Baseline	0.93	Lightening holes
Configuration L1	0.2	Bond-line as compared to the mating steel section
Configuration L2	0.2	Bond-line as compared to the mating steel section

The 2nd Bull Gear Configuration used a similar material system, form, and layup as the 1st configuration. The bonded joint at the outer gear rim was designed to have a similar shear area to applied load as the 1st configuration's bonded joint to reduce analysis time. Minimum margins of safety are shown in Table 6 based on initial sizing and corresponding stress analysis. Margins of safety for the bonded lap joints were written against the general strength of the bonded lap joint as compared to the strength of the bonded metallic section following guidance from Niu (Ref. 28). Equation (22) shows how margin of safety is calculated for the bond line.

$$MS^{(\text{adhesive})} = \frac{P_{\text{all}}^{(\text{adhesive})}}{P_{\text{all}}^{(\text{steel})}} - 1 \qquad (22)$$

Where P_{all} is the allowable load per inch in the corresponding adhesive layer required to carry the maximum load per inch in the mating metallic (steel) component, P_{max}.

6.3   Planet Gears

In order to assess how large scale composite hybrid rotor shaft designs may fit into smaller packages, such as bevel or spur gear shafts, a conceptual layout of a compound planet gear was developed. The concept modified a compound planet gear from the CPDD, see Section 5.4, in order to reduce weight of the baseline configuration.

The baseline compound planet gear is a more complex configuration, including three (3) integral, spur gears and two (2) integral bearing races. Starting at the bottom of the planet gear, the first spur gear meshes with a rotating Sun Gear and a fixed Ring Gear. Moving axial up the planet gear, an integral bearing race positions the planet gear radially and a bearing shoulder prevents the gear from moving axially down. The second and third spur gears mesh with counter-rotating ring gears that supply mechanical power to an upper and lower rotor head. At the top of the planet gear, the second integral bearing race positions the gear radially and axially in the opposite direction of the other bearing race.

The conceptualized hybrid compound planet gear includes similar external spur gears, except each gear is fabricated separately and assembled. Curvic splines are conceptualized at the faying surface interfaces between each gear and the assembly is preloaded to generate a stiff, compact design, see Figure 22. The first external spur gear meshes with the rotating Sung Gear and a fixed Ring Gear. Again, moving axial up the planet gear, a bearing race is integral with the first external spur gear, but is assembled with the second external spur gear. This bearing race, and associated shoulders position the gear radially and axially. The second and third external gears mesh with the same internal ring gears that supply mechanical power to an upper and lower rotor head, but positions along the shaft are switched to facilitate a stiffer load path for preload. At the top of the planet gear, the third external spur gear is clamped to the second external spur gear. The external spur gear is conceptualized to be similar to a typical planet gear/bearing assembly in that external gear teeth surround an internal, integral bearing race.
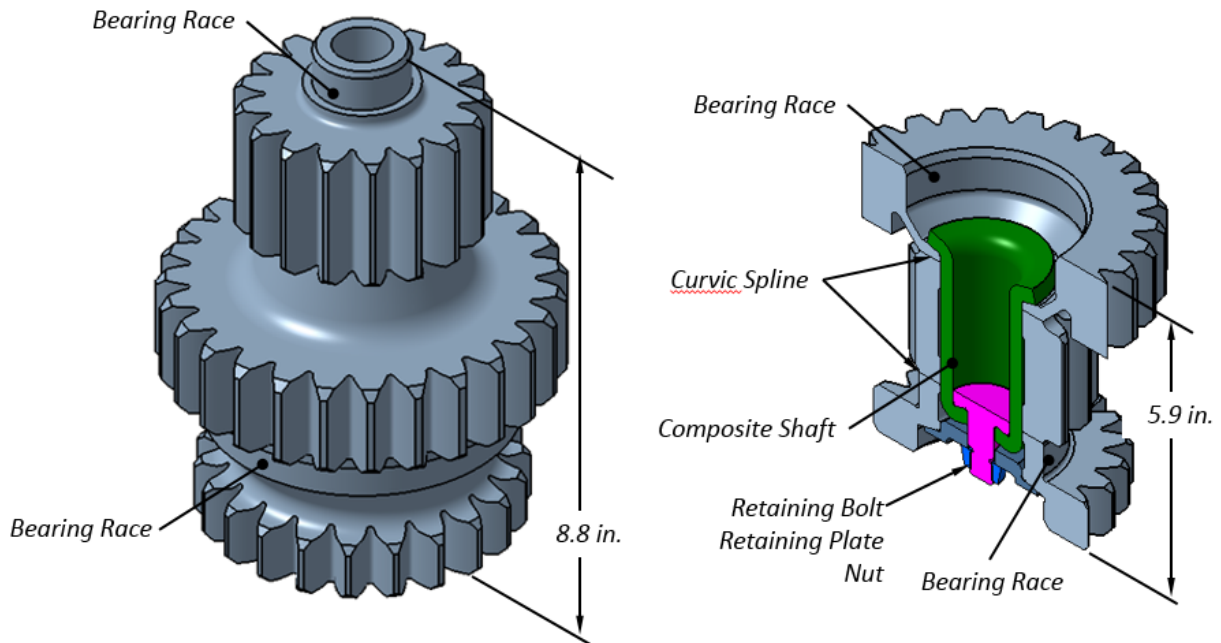
Figure 22.—Baseline compound planetary gear (left) and conceptualized hybrid compound planet gear (right).

The overall design is 2.9 in. shorter than the baseline configuration and 10 percent lighter than the baseline configuration. The reduced axial spacing between the 2nd and 3rd gear stages will reduce the bearing reaction loads resulting in a lighter carrier. Additionally, the reduced overall height will reduce the ring gear supports and overall height of the housing which is expected to reduce weight as well. The anticipated weight reductions for the ring gear supports, housing and carrier require additional investigation and have not been evaluated at this time.

6.4   Planet Carriers

Simple planetary systems are common-place within aerospace transmissions. Even configurations noted in this study with large bull gears commonly include at least one planetary system reduction stage. Planet carriers tend to be fabricated from high-carbon or low-alloy steels (4340 or 9310 steel, for example) and are stiffness critical designs in order to properly distribute gear loads among planetary gears, typically numbering between 3 and 6.

In order to simplify the estimation process an Aluminum Metal Matrix Composite (MMC) was found with a similar elastic modulus to steel. An initial search for stiff Aluminum MMC materials yielded a high strength and very high stiffness, A2024+55%TiB. A2024+55%TiB is an Aluminum MMC infiltrated with titanium boride (TiB), creating an elastic modulus of roughly 30 msi. Future design trade studies should consider the fracture toughness of A2024+55%TiB against other light materials. Current uses of other Aluminum MMC in aerospace includes bearing liners.

The percent weight savings of A2024+55%TiB planet carriers may be calculated directly by taking the ratio of the A2024+55%TiB density (0.131 lb/in.^{3}) over a typical steel density (0.284 lb/in.^{3}), resulting in a weight savings of 46 percent per planet carrier.

6.5   Composite Hybrid Components From Other Sources

Composite hybrid components that have recently been designed for alternate trade studies or development efforts were included in this study in order to add more data to the special features factor development. The composite hybrid components that were included in this study are the AH-64 Block II Apache Bull Gear and the CH-47 Block II Aft Rotor Shaft. The percent weight savings calculated for each configuration was included in the average percent weight savings used to develop the special features factor for each component.

The AH-64 Block II Apache Bull Gear was developed under the Research and Technology for Aerospace Propulsion Systems (RTAPS) Program. The development effort included analytical modeling of the bull gear rotating through mesh in order to develop more accurate loads at the gear rim. The Bull Gear consists of a metallic hub, and composite web, and a metallic gear rim. The composite web structure transmits shear and bending from the metallic gear rim, into the metallic hub. The composite web is co-bonded to each neighboring metallic structure (Ref. 29). The AH-64 Block II Apache Bull Gear is calculated to save 22 lb as compared to the existing design.

The CH-47 Block II Aft Rotor Shaft is being developed for use on the CH-47 Block II Aircraft. A sub-scale manufacturing trial specimen (Ref. 4) and a full-scale manufacturing trial specimen have been fabricated. Similar to the Configuration "L1" Rotor Shaft the CH-47 Block II Hybrid Rotor Shaft consists of three (3) pieces, a lower steel section, a composite center section, and a steel upper section. The composite center section is mechanically connected to the upper and lower steel sections through arrays of shear pins at the upper and lower interfaces. The CH-47 Block II Aft Rotor Shaft is calculated to save 55 lb as compared to the existing design.

7.0   Composite Hybrid Special Features Factor

Special features factors are used in Boeing's "Box-by-Box" parametric estimating methodology to distinguish design features that are known to affect the final weight a configuration, specifically in this case transmissions, rotor shafts, and drive shafts. Nominally, the special features factor is unitized and when a design feature is known to reduce the weight of the configuration, the special features factor is reduced.

Each hybrid composite component was grouped into the applicable category and each category developed a Delta Factor. The Delta Factor is based on the average percent weight savings in each category and process in Boeing's parametric estimating formulas. The Delta Factor is then subtracted from the baseline special features factor for each transmission configuration listed in Table 2. The two (2) configuration "L" rotor shafts were averaged with the CH-47 rotor shaft to develop a Delta Factor for composite shafts and Configuration L1, Configuration L2 Bull Gears were averaged with the AH-64 Block II Apache Bull Gear. The Planet Carrier weight savings was determined based solely on the ratio of material densities switching from steel carriers to A2024+55%TiB carriers. Table 7 summarizes the weight savings of each component and the average Delta Factor for the noted groups. The Delta Factor, and subsequent Special Features Factor, is used to estimate the weight of each transmission; the Delta Factor does not indicate the overall drive system weight savings. Overall drive system weight savings is estimated by combining weight savings seen at all major transmission and shaft assemblies. Section 9.0 includes a brief discussion regarding expected weight savings for the overall aircraft.

TABLE 7.—DELTA FACTOR SUMMARY

Classification	Title	Weight savings, lb	Delta factor
Rotor Shafts	Configuration L1	34	−0.06
	Configuration L2	88	
	CH-47 Aft Rotor Shaft	55	
Bull Gears	Configuration L1	34	−0.10
	Configuration L2	27	
	AH-64 Bull Gear	22	
Planet Carriers	(1)	(1)	(1)

Note: (1) All planet carrier percent weight savings were calculated as follows:

$$\frac{\rho_2}{\rho_1} = \frac{0.131\,\text{lb}/\text{in.}^3}{0.284\,\text{lb}/\text{in.}^3} * 100\% = 46\% \tag{23}$$

8.0 Parametric Weight Estimates of Hybrid Transmissions

Using the information developed during the component design and trade study phase (Section 6.0), the weights of transmissions with extensive use of composite materials in the rotating frame were parametrically estimated. In most cases, the Delta Factor of each component classification noted in Table 7 is applied to components with similar features and are summed and then added to the baseline Special Features Factor of each transmission configuration noted in Table 2.

The Configuration "L" Block Diagram, CH-47 Block II Aft Transmission, and AH-64 Block II Apache used the calculated weight savings for each, respective component. 88 and 34 lb weight savings were assumed for the Rotor Shaft and Bull Gear, respectively, in the Configuration "L" Block Diagram. The CH-47 Block II Aft Transmission was assumed to save 55 lb in the Rotor Shaft (Ref. 4), and the AH-64 Block II Apache was assumed to save 22 lb in the Bull Gear. Composite hybrid components were also assumed to be included in addition to the noted component configurations designed for the Configuration "L" Block Diagram, CH-47 Block II Aft Transmission, and AH-64 Block II Apache.

A listing of all of the hybrid components proposed for each transmission configuration is shown in Table 8. The Delta Factor developed for Rotor Shafts was also applied to Planet Gears and Bull Pinion Shafts. The Delta Factor developed for Bull Gears was also applied to Planet Gear Webs and Bull Pinion Webs. The corresponding baseline and hybrid transmission weight estimates and the estimated weight savings are shown in Table 9.

The weight savings results from Table 9 are displayed graphically in Figure 23 and Figure 24. Figure 23 shows the percent weight savings as a function of baseline weight and transmission configuration. Figure 24 graphs weight vs power-speed index for baseline and hybrid transmission configurations. Figure 24 includes two (2) different sets of power-speed index trends. Each set contains a baseline and a hybrid trend, wherein the baseline trend includes all of the baseline transmission weight estimates as compared to power-speed index and the hybrid trend includes all of the hybrid transmission weight estimates as compared to power-speed index. The first set includes all positive power-speed indices; however, it was observed that the trend lines were very sensitive to two (2) outliers, the CH-53K and Mi-26 Transmissions. Adjusted Trends were plotted alongside the unadjusted trends to show the sensitivity to the CH-53K and Mi-26 Transmission Configurations. The Adjusted Trends include the Baseline and Hybrid Trend Lines up to power-speed indices of 35.

The "K" factor for the Baseline Trend and the Adjusted Baseline Trend differs by eight (8) points. Brown suggests that the "K" factor is reduced by 24 points over a 20 year period (Ref. 14). The difference between "K" in the Baseline Trend and Adjusted Baseline Trend represents nearly roughly a decades worth of weight savings technology due to hyper-sensitivity of transmission with higher power-speed indexes.

In example, reducing the weight of the Mi-26 Main Transmission by 100 lb reduces "K" by 0.5 points; however, reducing the OH-58 Main Transmission by a similar 100 lb reduces "K" by 0.01 points. Even through the percent weight savings in this example is substantially greater for the OH-58, the difference in "K" is negligible, but a small percent weight savings for Mi-26 results in a notable swing in trends.

The difference in "K" for higher power-speed indexes supports the use of the Adjusted Baseline. "K" for the Baseline Trend and Adjusted Baseline Trend is 75 and 83, respectively, an eight (8) point swing by omitting two (2) data points. Future system studies may incorporate more transmissions in the higher 70 to 80 Power-Speed Index class in order to reduce sensitivity to any single adjustment.

TABLE 8.—HYBRID COMPONENTS APPLIED TO PARAMETRIC WEIGHT ESTIMATES

Type	ID	Title	Proposed hybrid components applied to hybrid parametric weight estimates
Simple Planetary	A	CH-47F Block II Aft Transmission	Rotor shaft and 1st and 2nd stage planet carriers
	B	OH-58 Main Transmission	Rotor shaft and planet carrier
Compound Planetary	C	RITA Transmission	Rotor shaft, planet carrier, and planet gears (6X)
	D	CPDD	Planet gears (12X)
	E	SABP Transmission	Rotor shaft, planet carrier, and planet gear shafts/webs (4X)
----------	F	Proprietary Transmission Configuration	---
----------	G	PSU Pericycler	Rotor shaft and nutating gear carrier
Prop-Rotor Configuration	H	LCTR2 Prop-Rotor Transmission	Prop-rotor shaft, planet carrier, and bull gear
	J	V-22 Prop-Rotor Transmission	Prop-rotor shaft, 1st and 2nd stage planet carriers, and bull gear
	K	Bell ART II Transmission	Prop-rotor shaft, planet carrier, bull gear web, and bull pinion shafts
Large Bull Gears	L	Bull Gear Block Diagram	Rotor shaft, bull gear, and bull pinion shafts (4X), 2nd stage reduction spur gear webs
	M	AH-64D Main Transmission	Rotor shaft, planet carrier, and bull gear
	N	RAH-66 Main Transmission	Rotor shaft, bull gear, and bull pinion shafts (4X)
	P	UH-60 Main Transmission	Rotor shaft, planet carrier, and bull gear
	R	CH-53K Main Transmission	Rotor shaft, bull gear, and bull pinion shafts (12X), 2nd stage reduction spur gear webs (12X)
	S	Mi-26 Main Transmission	Rotor shaft, bull gear, bull pinion shafts (12X), and RH and LH engine input shafts

TABLE 9.—PARAMETRIC WEIGHT ESTIMATES FOR BASELINE AND HYBRID TRANSMISSIONS

| Type	ID	Title	Baseline transmission weight, lb	Hybrid transmission weight, lb	Transmission weight delta, lb
Simple Planetary	A	CH-47F Block II Aft Transmission	2255.7	2087.0	−169
	B	OH-58 Main Transmission	99.9	90.4	−10
Compound Planetary	C	RITA Transmission	1861.3	1658.0	−203
	D	Compound Planetary Differential Drive	1654.5	1451.0	−204
	E	SABP Transmission	243.3	225.0	−18
--------------	F	Proprietary Transmission Configuration	1604.8	1452.0	−153
--------------	G	PSU Pericycler	1718.7	1606.9	−112
Prop-Rotor Configuration	H	LCTR2 Prop-Rotor Transmission	1892.8	1774.0	−119
	J	V-22 Prop-Rotor Transmission	795.4	724.0	−71
	K	Bell ART II Transmission	684.5	607.0	−78
Large Bull Gears	L	Bull Gear Block Diagram	704.6	621.0	−84
	L	Bull Gear Block Diagram	1087.7	959.0	−129
	L	Bull Gear Block Diagram	1447.8	1276.0	−172
	M	AH-64D Main Transmission	680.8	633.6	−47
	N	RAH-66 Main Transmission	542.2	514.7	−28
	P	UH-60 Main Transmission	1343.6	1220.9	−123
	R	CH-53K Main Transmission	3932.8	3617.0	−316
	S	Mi-26 Main Transmission	6612.0	6214.0	−398
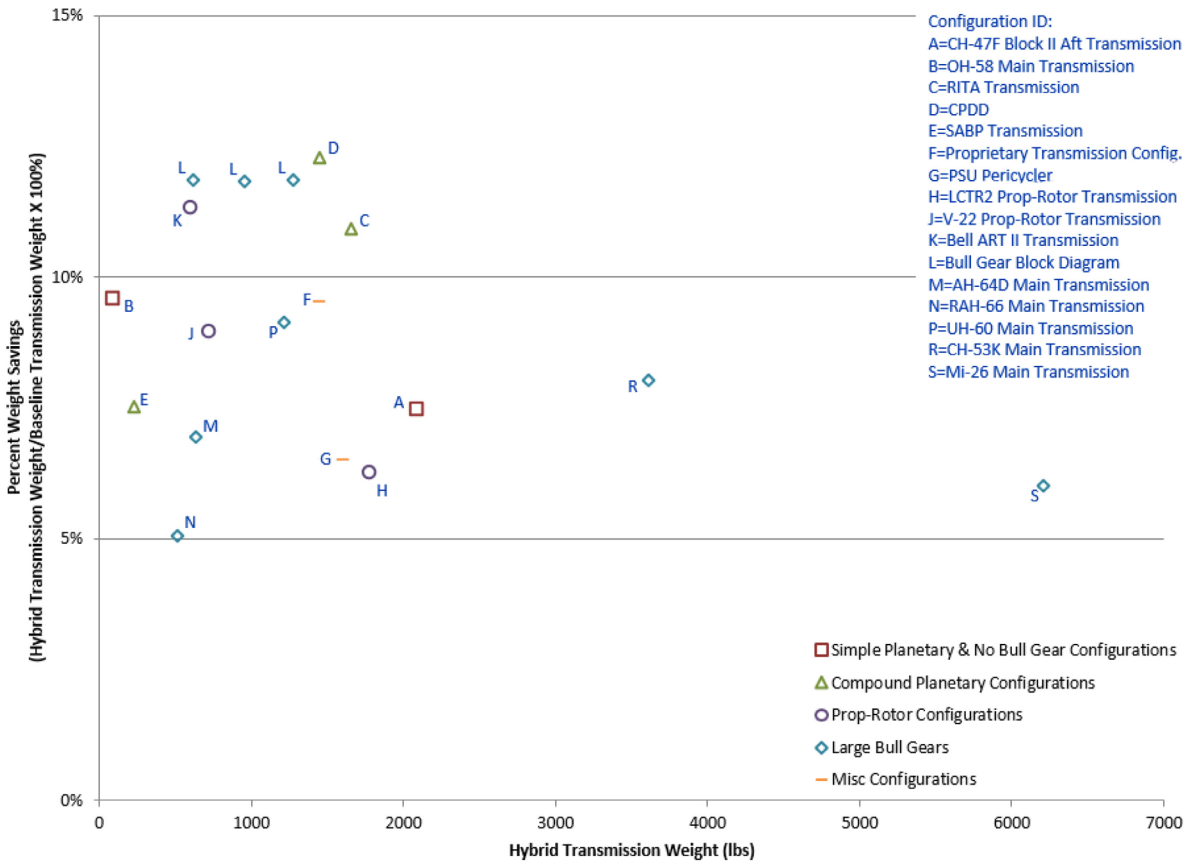
Figure 23.—Percent Weight Savings vs. Hybrid Transmission Weight.
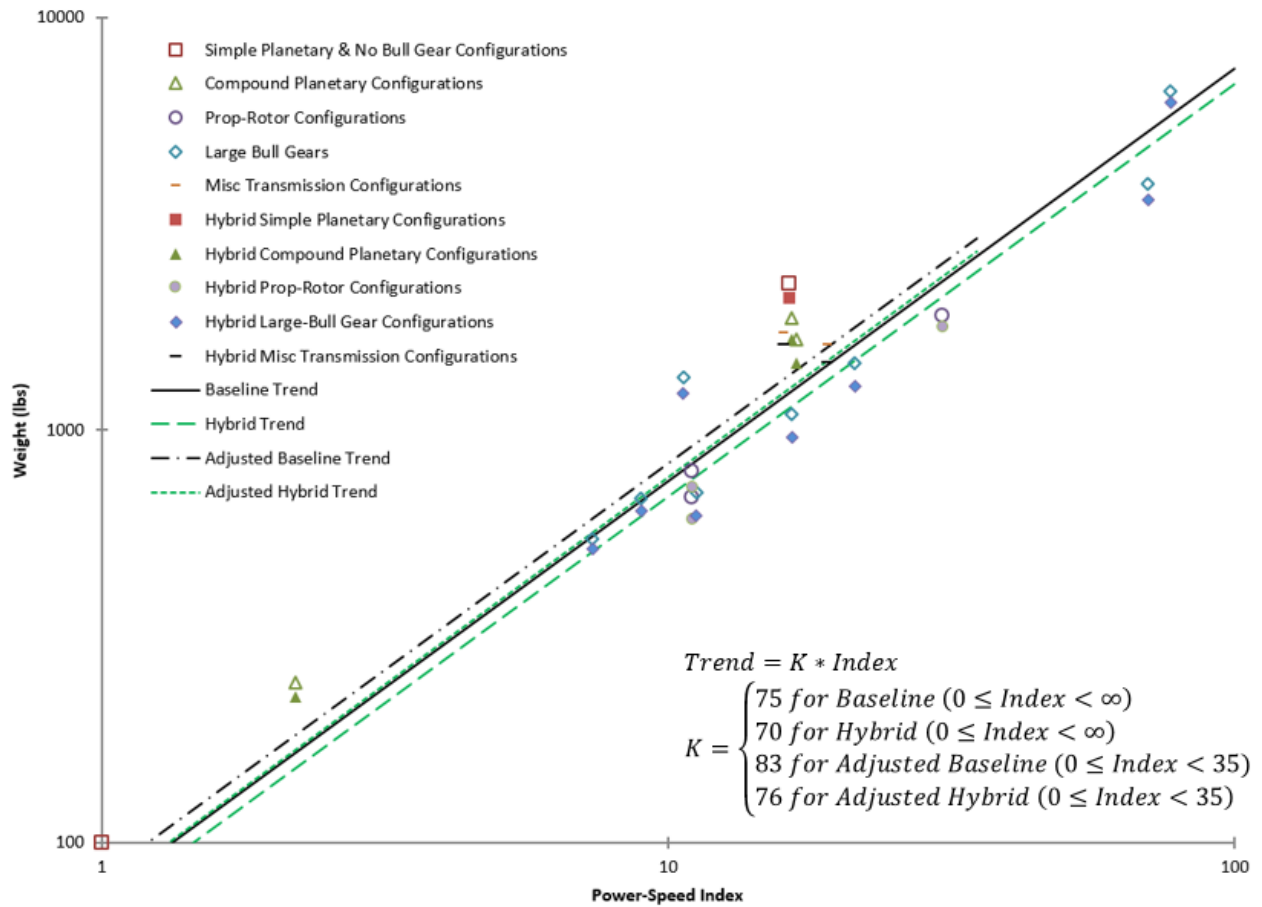
Figure 24.—Weight vs. Power-Speed Index.

9.0   Discussion

Parametric weight estimates of the noted helicopter transmissions with extensive use of composite materials in the rotating frame generated an average 9 percent weight savings over the baseline transmission. Simple and compound planetary systems generated an average 10 percent weight savings and transmissions with large bull gears generated an average 9 percent weight savings. The maximum percent weight savings observed was in the Compound Planetary Differential Drive (CPDD).

The CPDD included the final two (2) gear reduction stages of a typical three (3) stage reduction transmission. Under future development efforts it is likely that one or more bevel gear meshes will be included to reduce speed and direct power into the parallel axis CPDD gear train. The addition of one (1) or more bevel gear meshes will reduce the percent weight savings observed if further design studies are undertaken. Future design work may be able to extend the application of composite materials into bevel gear shafts. Bevel gear shafts were not included in this study due to schedule and budgetary restrictions, but lessons learned from component designs may be applied to bevel gear shafts to further reduce weight deltas.

Also, it is important to note the difference between the 10 percent weight savings estimated for the CPDD compound planet gear (Section 6.3) and the 204 lb (12 percent) weight savings estimated for the CPDD Transmission (Table 9). While it is unlikely that the compound planet gears will generate a 204 lb weight savings, it is important to consider that the parametric estimating method accounts for the compound planet gear weight, bearing weight, carrier weight, output gearing weight, and housing weight. Carrier weight and output gearing weight will be reduced by designing more compact planet gears, and housing weight will be reduced through more compact designs, as well. Further, the more flexible packaging of the compound planet gear assembly may result in smaller face widths and lighter bearings due to stiffer supporting structure at the gear heads and reduced bending moments at the effective bearing centers. It is recommended that future work down-selects specific transmission configurations to design one (1) or more hybrid transmission to further validate parametric weight estimates.

In configurations like the CPDD or LCTR2, where modifications to supporting structure, landing gear, etc. may be made, even greater weight savings will be observed when considering the noted supporting structure. During initial aircraft sizing, aerodynamic performance characteristics, such as hover performance, are used to size the rotary wing blades, heads, transmissions, and engines which are then flowed down into the landing gear, fuel cell, and airframe. Once initial weight estimates of all of the dynamic and static components are complete, the design organization may begin to iterate, adding more power to overcome initial assumptions or reducing aircraft weight to meet payload targets. Prior design history within Boeing, Philadelphia has shown that a one (1) lb weight delta within the iteration loop will lead to a 2 to 2.5 lb weight delta in the aircraft's empty weight. Figure 25 shows a graphic representing the iteration loop during aircraft sizing.

Considering the LCTR2 Prop-Rotor Transmission, an estimated 595 lb weight savings is likely to be observed in the aircraft's empty weight if the Prop-Rotor Transmissions design includes use of composite materials into the rotating frame. The estimated weight savings of the LCTR2 Prop-Rotor Transmission is 119 lb (Table 9); however, when considering the aircraft empty weight, the design organization must consider that there are two (2) Prop-Rotor Transmissions included in the LCTR2 aircraft configuration (Ref. 3). Then, applying the weight delta from the iteration loop, it is safe to assume that 2.5 lb will be saved for every one (1) lb reduction in transmission weight; therefore, 595 lb is likely to be saved if the Prop-Rotor Transmissions extensively use composite materials within the rotating frame. Considering the mid-wing gearbox and the torque path to the interconnecting shafts within the Prop-Rotor Transmissions, additional weight savings may be expected.
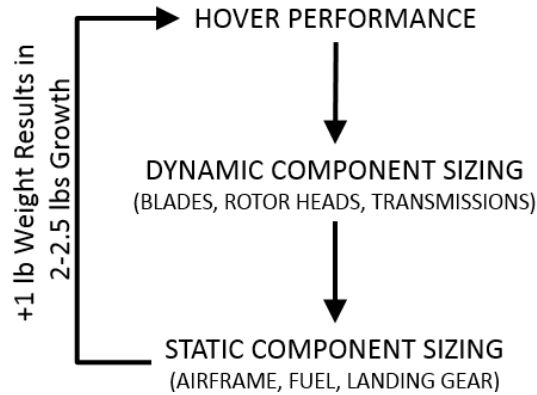
Figure 25.—Aircraft Sizing Iteration Loop.

Similar weight savings may be observed in other conceptual aircraft configurations. All tandem and tilt-rotor aircraft will see a two-fold benefit in the transmission weight savings noted in Table 9 due to similar transmissions in the front and back of the helicopter or left and right, respectively. Tandem and tilt-rotor configurations include the CH-47, RITA, LCTR2, V-22, Bell ART II, and potentially the Configuration "L" Bull Gear Block Diagram may be incorporated into future tandem configuration. Most of the transmission configurations included in this study are intended for use on aircraft that are currently fielded, so it is more difficult to assume the full 2.5 lb weight savings from the iteration loop; however, programs such as the CH-47F and CH-53K have shown that large changes to the supporting airframe structure may be made during the lifecycle of a fielded aircraft.

The technical approach developed to generate performance benefits across a wide variety of helicopter configurations and power classes led to a more conservative method to estimate the Delta Factor applied to the Special Features Factor in the parametric estimating formulas. Averaging the component weight savings to develop the Delta Factor (Section 7.0) reduced the sensitivity of the parametric weight estimates to unresolved technical challenges. More accurate weight estimates may be developed when designs are developed and tested.

10.0   Engineering Challenges

Special Features Factor development used a conservative method of averaging various component designs in order to provide high confidence weight estimates. This method of averaging designs was intended to cover unknown technical challenges that would be discovered during the component design and trade study phase (Section 6.0). The component design and trade study phase helped identify technical challenges faced by the designer. Other technical challenges will arise in the future, but preliminary findings are detailed below with corresponding recommendations for future work made in Section 12.0.

When initially compiling and organizing technical challenges and corresponding tasks, it quickly became evident that technical challenges were not the only challenges that had to be overcome to develop composite hybrid gears. Overarching engineering challenges exist that include funding, schedules, and risk management; all elements that are not technical in nature, but are challenges that must be overcome to develop new technologies.

Engineering challenges are broken into non-recurring engineering challenges, framing how program risk and development milestones must be properly planned, and design challenges, identifying the technical risks that were identified during the component design and trade study phase including identified risks in fielding and maintaining components.

10.1　Non-Recurring Engineering Challenges

Major aircraft programs, such as the AH-64E or CH-47F Block II, generally include large development budgets that are able to absorb varying levels of technology insertion. However, major aircraft programs typically do not incorporate the timeline required for long-lead procurement subsystems, like transmissions, to develop and insert new technologies.

Engineering has to balance flight test schedules and development time-lines with performance gains, making it difficult for immature technologies to be incorporated into a major aircraft program. Building confidence early in a new technologies life is of the upmost importance in order for engineering to assume measured amounts of risk with flight test looming.

New transmission development typically occurs over a 3 to 5 year time span with limited technology insertion on the final product. While not a directly linear relationship, the more technology that's incorporated into a subsystem design, the longer the development effort. It is recommended that composite hybrid gear technology development continues to progress through sub and full-scale testing with direct Original Equipment Manufacturer (OEM) involvement prior to incorporating into a major aircraft program.

10.2　Design Challenges

Multiple design challenges were identified during this study as well as by utilizing published research. The major areas of interest are in mechanical interfaces such as threads and splines, temperature effects, temperature effects, inspection, and fault detection challenges.

10.2.1　Mechanical Screw Threads

Mechanical screw threads are considered a technical challenge; however, it is believed that solutions may be developed to solve the mechanical screw thread design problem. For example, a locknut design was conceptualized for hub retention hub retention on the Configuration L3 Rotor Shaft (Section 6.1).

Two hemispherical locknut halves are placed around the upper cone seat with satellite bolts installed. Once in place, a sleeve is pressed over the locknut to keep the two (2) halves together and a retaining ring is installed to retain the sleeve and the satellite bolts are torqued to preload the hub stackup. Figure 26 shows the installation process.
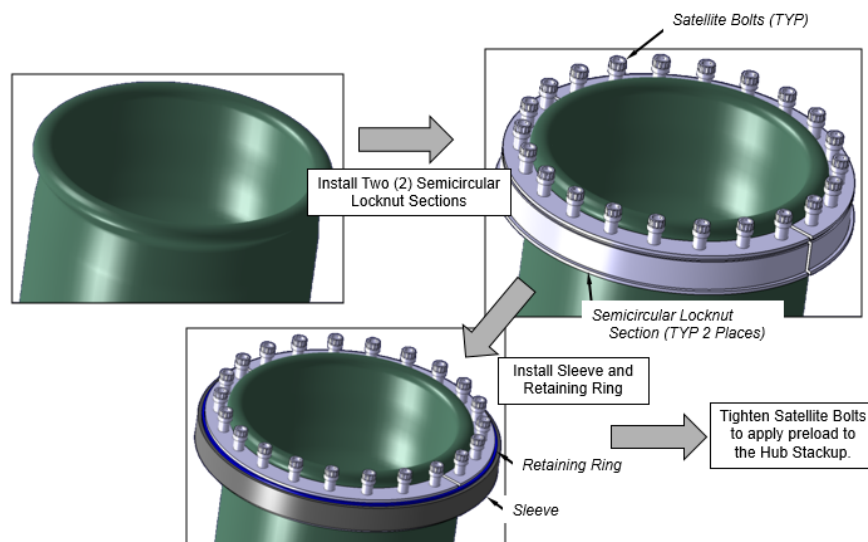

Figure 26.—Installation of Threadless Locknut.

10.2.2 Involute Spline Arrays

Involute Spline Arrays were identified as areas that may be difficult to design in composite hybrid components. Transmitting torque and bending from one (1) component and into a composite shaft has been demonstrated over years of service history.

Both the M360 and RAH-66 avoided using splines in composite structure through the use of novel design features to replace fixed splines. Based on past experience, fixed splines may be overcome through detailed design of interlocking mechanical features.

Working splines which are used to facilitate installation and removal of specific components. Replacing working splines is a design challenge that requires follow-on work.

Composite splines are in use in a wide range of helicopter transmissions and turbine engines for low power applications. Torlon muffs are used for spline adapters in low lubrication environments with mixed results (Ref. 30). Cracking of splined adapters and excessive wear are characteristic of these components.

Recent research has included features that are similar in function to a typical spline joint, but incorporate lobed features in place of fine pitch spline teeth. These lobed features may be conceptualized as coarse pitch spline teeth, specifically designed to balance bending and wear stresses in the composite and metallic components (Refs. 1 to 9). Sub-scale loss of lubrication testing has shown that coarse splines (lobes) require discrete design studies to support load at elevated temperatures (Ref. 9). Refinement of the lobe design and full-scale testing has shown that coarse splines (lobes) may be designed to transmit torque at typical transmission temperatures and speeds, but with positional accuracy waning as testing progressed, see Section 10.2.3.

Sub-scale and full-scale design and testing is recommended to demonstrate the strength of a composite spline or lobe interfaces. Endurance testing of subscale specimens is recommended. Full scale testing using backlash measurements has previously been utilized to characterize wear over time (Ref. 30) which may be extended to include gear patterns to characterize composite/metallic joint degradation over time.

10.2.3 Temperature Effects

Temperature effects were not covered in this study, but are critical to introduce new materials into transmission systems. Three (3) technical challenges have been identified that should be overcome prior to fielding composite hybrid dynamic components. First, the coefficient of thermal expansion mismatch between steel and composite materials must be considered during normal operation, including typical hot and cold days. Second, emergency conditions should be considered. Third, long term material compatibility, sush as creep, should be addressed. GRC has performed composite hybrid gear testing in two (2) related studies which highlighted or focused on two (2) of these issues.

GRC has built and tested a full-scale composite hybrid gear in the GRC High-Speed Helical Rig (Ref. 1). Testing found that "orbiting" of the gear rim occurred. "Orbiting" of the gear rim will create issues at the gear teeth and vibration issues that may propagate to bearings and structural supports. GRC has demonstrated unexpected results in loss-of-lubrication testing (Ref. 9). In the comparative loss-of-lubrication test one (1) composite hybrid gear mated with one (1) all steel gear performed substantially better than two (2) mating steel gears.

GRC reported that a black, fluid substance was observed on the composite hybrid gear during testing. Post-test evaluation indicated that the black substance on the gear teeth is likely either the epoxy matrix material or thin film adhesive used to fabricate the composite web.

Future work should include analysis and testing of temperature and material compatibility effects inside helicopter transmissions to simulate life cycle environments and degradation. Coefficient of thermal expansion mismatches and ply compression or crushing should be analyzed at high temperatures.

Further testing should be performed to understand how various matrix materials and adhesives effect operating on hot days and emergency conditions. Further research and testing should include long-term material compatibility assessments, including mechanical creep in oil-wet environments.

10.2.4 Inspection Challenges

Typical helicopter transmissions today are considered to require only condition based maintenance. This means that a transmissions may be operating in the field for years, if not decades, before returning to an overhaul facility for inspections. New technology must be robust and able to continue safe operation for an unlimited amount of time. However, composite failure modes are not always identifiable via visual inspection.

Two (2) methods have been identified to provide safe operation in any condition. The first design method is to design mechanical, robust, fail-safe features. The second method is to incorporate diagnostic equipment to alert pilots and crews of degrading component or system performance, prior to a catastrophic event.

It is recommended that as part of sub-scale and full-scale testing efforts, detailed inspection methods for both overhaul facilities and field maintainers are developed early in the design process. Composite hybrid gears are new technology in a critical application, requiring a detailed understanding of failure modes and failure prevention.

10.2.5 Fault Detection Challenges

Existing defense and commercial helicopters typical have electrified debris screens or chip detectors to alert the crew when metallic debris is detected within the transmission. As greater mixes of materials are introduced inside helicopter transmissions the systems will become less effective.

It is recommended that future work includes developing methods or techniques to monitor non-metallic, non-magnetic debris that is generated prior to a catastrophic failure. These systems should be reliable, easy to maintain, and relatively simple in their operation, similar to the incumbent electrified debris screens and chip detectors. Additionally, composites allow for imbedded sensors that may be investigated in future work.

11.0 Summary and Conclusions

A systems level technical approach was developed based on existing designs, preliminary technical challenges, and material selection guidance. The technical approach took transmissions from a multitude of rotorcraft configurations and power classes to build a database of expected performance gains. The technical approach focused on development of a Special Features Factor to be applied to composite hybrid shafting and composite hybrid gear webs parametric weight estimates.

Composite materials are in use in today's helicopter propulsion systems. Rotor blades, rotor shafts, and drive shafts all utilize composite materials in various applications. Composite materials provide inherent weight saving properties that are underutilized inside today's helicopter transmissions.

A total of sixteen (16) transmissions were studied. Simple and compound planetary systems, prop-rotor transmissions, and transmissions with large, split-torque bull gears were included in this study.

Composite hybrid component designs were explored in order to generate a database to develop Special Features Factors for composite hybrid components. A Special Features Factor was developed for composite hybrid rotor shafts that was applied to smaller scale gear shafts, as well, and a Special Features Factor was developed for composite hybrid parallel axis gear webs.

Parametric weight estimates of rotorcraft transmissions with extensive use of composite materials in the rotating frame generated an average 9 percent weight savings over the baseline transmission. Simple and compound planetary systems generated an average 10 percent weight savings and transmissions with large bull gears generated an average 9 percent weight savings. The maximum percent weight savings observed was 12 percent in the Compound Planetary Differential Drive (CPDD).

Rotorcraft that are able to modify structures supporting transmission systems will see greater performance benefits. If stationary structure may be designed or redesigned with a transmission, an aircraft's empty weight may be reduced by 2 to 2.5 lb for every 1 lb saved in the transmission.

The LCTR2 Large Civil Tilt-Rotor was calculated to save 595 lb by utilizing composite hybrid components inside the Prop-Rotor Transmission in the rotating frame. Additional weight savings is expected if the mid-wing gear box is included.

As composite hybrid technology matures additional weight savings may be observed as compared to the weight savings estimated provided herein. The technical approach utilized an averaging method to reduce the sensitivity to any single configuration. By doing so, weight estimates generated in this study are more likely to capture weight penalties associated with engineering challenges.

Engineering challenges include non-recurring engineering challenges and design challenges. Non-recurring engineering challenges include development time, cost, and risk assessments which could prevent new technologies from being included in new aircraft programs. Design challenges include designing mechanical interfaces, temperature considerations, inspection challenges, and fault detection challenges.

12.0   Recommendations for Future Work

It is recommended that composite hybrid gear technology development continues to progress through sub and full-scale testing with direct Original Equipment Manufacturer (OEM) involvement to mature technology and enable incorporation into a major aircraft program.

Sub-scale and full-scale design and testing is recommended to demonstrate the strength of a composite spline or lobe interfaces. Endurance testing of subscale specimens is recommended. Full scale testing using backlash measurements has previously been utilized to characterize wear over time (Ref. 30) which may be extended to include gear patterns to characterize composite/metallic joint degradation over time.

Future work should include analysis and testing of temperature and material compatibility effects inside helicopter transmissions to simulate life cycle environments and degradation. Coefficient of thermal expansion mismatches and ply compression or crushing should be analyzed at high temperatures. Further testing should be performed to understand how various matrix materials and adhesives effect operating on hot days and emergency conditions. Further research and testing should include long-term material compatibility assessments, including mechanical creep in oil-wet environments.

It is recommended that as part of sub-scale and full-scale testing efforts, detailed inspection methods for both overhaul facilities and field maintainers are developed early in the development process. Composite hybrid gears are new technology in a critical application, requiring a detailed understanding of failure modes and failure prevention.

It is recommended that future work includes developing methods or techniques to monitor non-metallic, non-magnetic debris that is generated prior to a catastrophic failure. These systems should be reliable, easy to maintain, and relatively simple in their operation, similar to the incumbent electrified debris screens and chip detectors. It is recommended that imbedded sensing technology is explored, utilizing the layup procedure of typical composite structures to place sensors in optimized locations for early fault detection.

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