Gear Design Effects on Performance of High-Speed Helical Geartrains as Used in Aerospace Drive Systems

Robert Handschuh, Charles J. Kilmain, Ryan T. Ehinger, and Eric A. Sinusas

The performance of high-speed helical geartrains is of particular importance for tiltrotor aircraft drive systems. These drive systems are used to provide speed reduction/torque multiplication from the gas turbine output shaft and provide the necessary offset between these parallel shafts in the aircraft. Four different design configurations have been tested in the NASA Glenn Research Center, High-Speed Helical Geartrain Test Facility. The design configurations included the current aircraft design, current design with isotropic superfinished gear surfaces, double-helical design (inward and outward pumping), increased pitch (finer teeth), and an increased helix angle. All designs were tested at multiple input shaft speeds (up to 15,000 rpm) and applied power (up to 5,000 hp). Also two lubrication, system-related, variables were tested: oil inlet temperature (160–250° F) and lubricating jet pressure (60–80 psig). Experimental data recorded from these tests included power loss of the helical system under study, the temperature increase of the lubricant from inlet to outlet of the drive system and fling-off temperatures (radially and axially). Also, all gear systems were tested with and without shrouds around the gears.

The empirical data resulting from this study will be useful to the design of future helical geartrain systems anticipated for next-generation rotorcraft drive systems.

Introduction

Rotorcraft drive systems are critical to the high efficiency and lightweight requirements of the propulsion system. Tiltrotor aircraft, as currently designed, utilize the drive system as a means to fly — even when one engine is inoperative through the use of shafting and other gearboxes to connect the two rotors together. A sketch of the entire propulsion system is shown (Fig. 1) and a close-up of the wing-tipped nacelle propulsion system is shown in further detail (Fig. 2) (Ref. 1).

Also in a tiltrotor aircraft, the entire propulsion system is required to tilt from the vertical position (helicopter mode) to that of the horizontal position (forward flight — airplane mode). These unique capabilities allow this aircraft to fly at a high rate of speed in the airplane mode and land vertically, greatly enhancing the aircraft's usefulness in fulfilling a number of military missions.

The drive system contained within the prop-rotor gearbox connects the parallel shafts of the gas turbine engine to that of the propeller via a geartrain of helical gears. The geartrain operates at high rotational speeds that produce high pitch line velocity of the gears that can affect the overall drive system

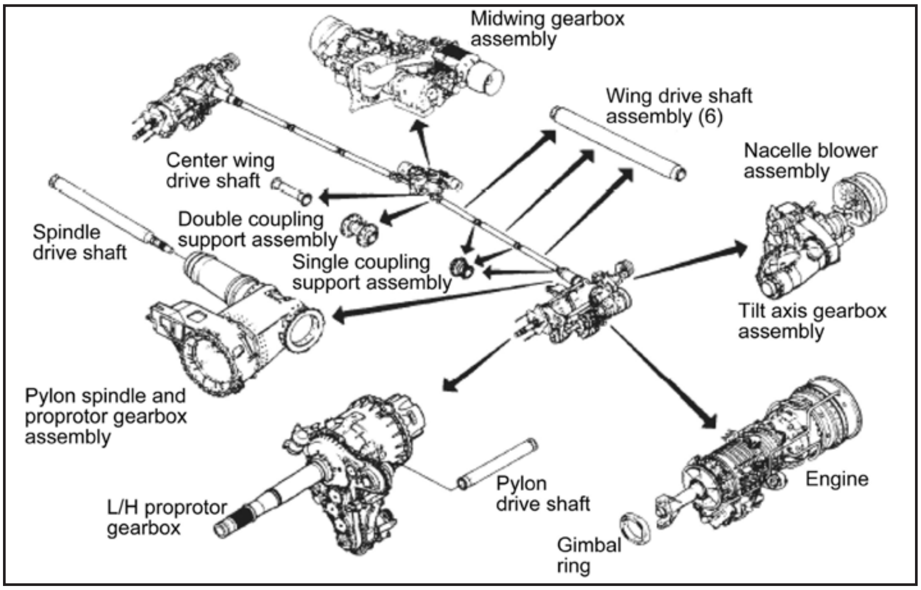

Figure 1 Tilt rotor propulsion system components (Ref. 1).

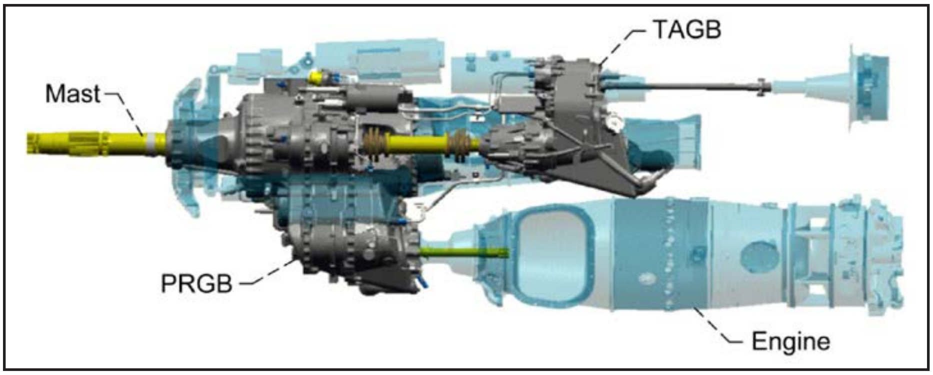

Figure 2 Propulsion system components that reside within aircraft nacelle — tilt axis gearbox (TAGB), and prop-rotor gearbox (PRGB).

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performance through an increase in windage power losses *(Windage is the air resistance of a moving object, such as a vessel or a rotating machine part, or the force of the wind on a stationary object.)*. It is of the utmost importance for drive system efficiency to make the transition from the gas turbine engine to the propeller with the minimum amount of power loss. High power loss is absorbed by the lubricant, or expelled through the gearbox housing in the form of heat. Therefore improved performance of the gearbox can result in more power available to the rotor, increased load capacity, or extended range.

The objective of this study is to experimentally determine how operating conditions, gear design, and gear shrouding can influence the performance of high-speed helical gear trains, as used in tiltrotor aircraft.

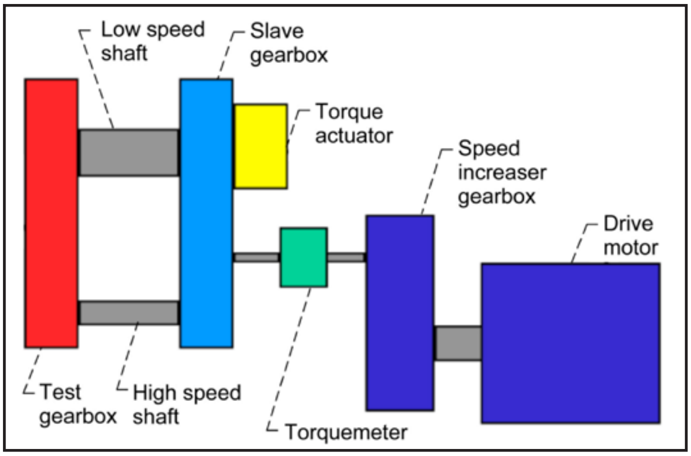

Figure 3 Test facility arrangement.

Test Facility, Test Hardware and Test Method

Test facility. The test facility used in this study is the high-speed helical geartrain test facility located at NASA Glenn Research Center just outside Cleveland, OH (Ref. 2). The test facility arrangement is shown (Fig. 3), as is a sketch of the key test system components (Fig. 4).

Referring to Figure 3 for the discussion, the facility operates as a closed-loop test facility. Power is circulated from the test gearbox to the slave gearbox and then returns to complete the torque loop. A rotating torque actuator in the slave gearbox provides an adjustable loop torque while the drive motor must provide for all of the gear, bearing, and windage losses. With the current components, up to 5,000 hp can be circulated around the test to the slave gearbox loop. The high-speed shaft, simulating the power turbine shaft, can be rotated to 15,000 rpm. Most of the test conditions that will be reported in this paper have to do with the hover and forward flight speed conditions. The drive system input shaft rotates at 15,000 and 12,500 rpm, respectively, at these conditions. Both gearboxes have separate lubrication systems that include supply and scavenge pumps, filters (3 μm), heaters, heat exchangers, etc. The test and slave gearboxes operate in a dry sump mode where the lubricant that is jet-fed to the gears and bearings is removed immediately after lubricating and cooling via the scavenge pumps. For all the data presented in this report, the slave gearbox operating conditions were constant, at ~160° F lubricant inlet temperature, and ~80 psi jet pressure.

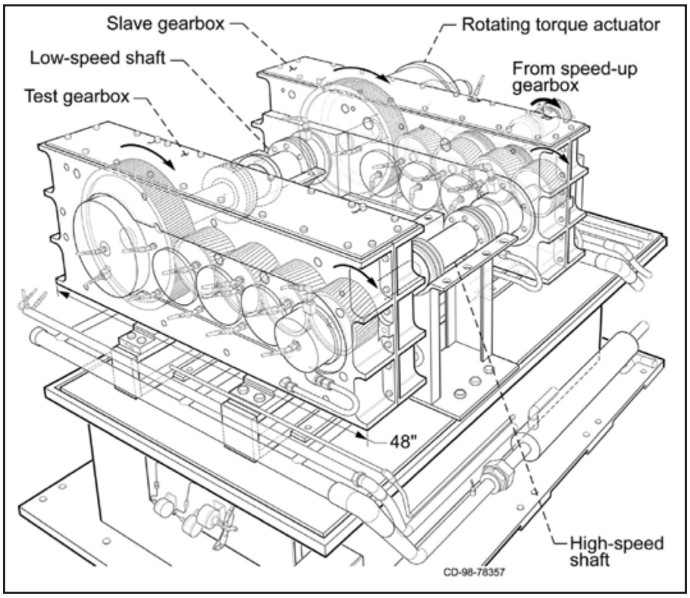

Figure 4 Sketch of test facility primary components.

Figure 5 Photograph of input gear designs; baseline, baseline + ISF, double-helical, fine pitch, and increased helix angle.

Test hardware. The gearing components used in the test program included four different gear designs. There is the baseline (currently used aircraft design), baseline with isotropic superfinishing (ISF), double-helical, fine pitch, and increased helix angle designs. The design information for all four cases is provided in Table 1. The same gear material, Pyrowear 53, was used in all gearing components and all were manufactured with the same surface finish and gear quality. A photograph of the input gear designs is shown (Fig. 5). The gearing components are shown dur-

Table 1 Basic gear design information

	Baseline design	Double helical design	Fine pitch design	Increased helix angle design
Number of teeth, input and 2nd idler/lst and 3rd idler/bull gear	50/51/139	50/51/139	70/73/196	50/51/139
Normal module, mm, (diametral pitch, (1/in.))	3.033 (8.375)	2.540 (10.000)	2.142 (11.858)	2.9136 (8.7177)
Face Width, mm (in.)	66.68 (2.625)	78.23 (3.08)	66.68 (2.625)	66.68 (2.625)
Normal pressure angle, deg.	20	20	20	20
Transverse helix angle at pitch diameter, deg.	12	35	12	20

Figure 6 Baseline test hardware during installation.

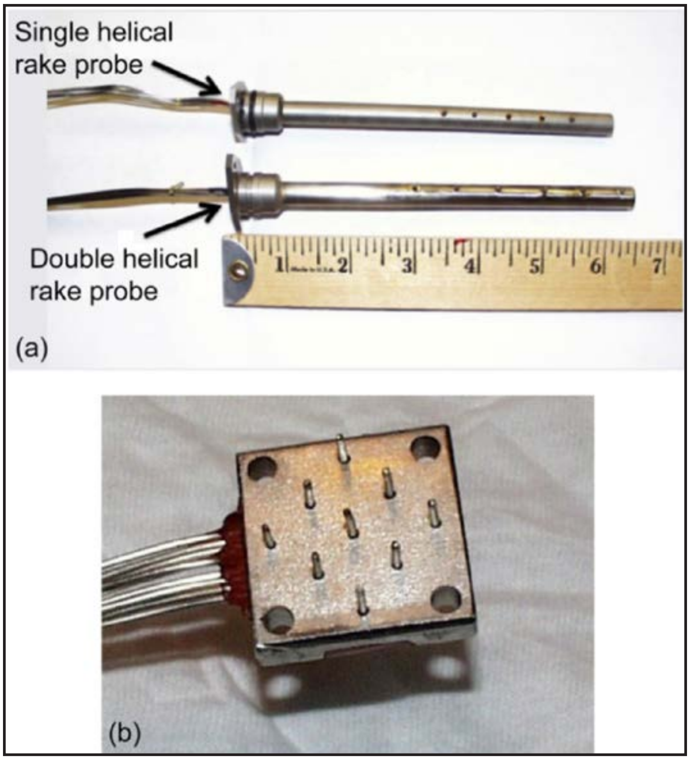

Figure 7 Rake probes (a) and array probe (b).

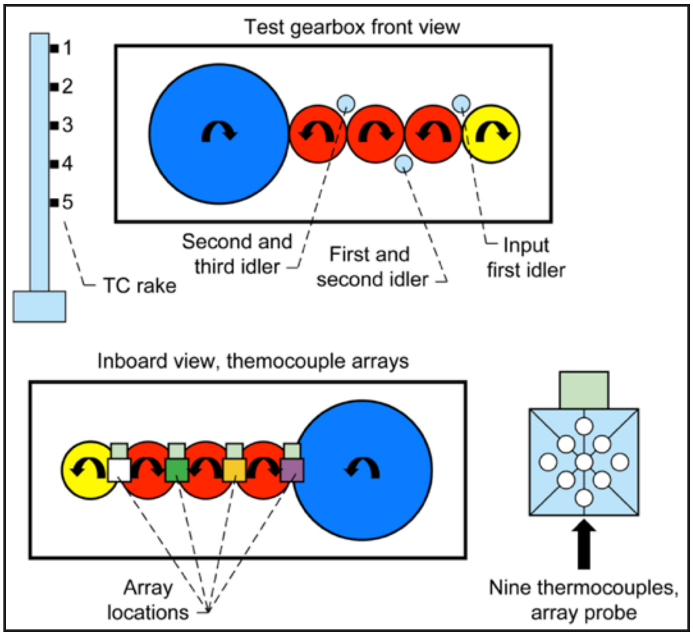

Figure 8 Locations of the rake (a) and array (b) probes in test gearbox.

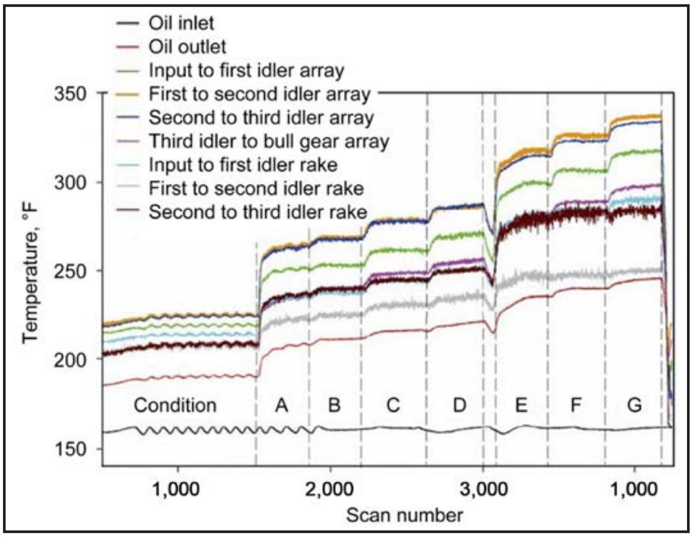

Figure 9 Temperature data at mid-face of rake and at array probe center for all sensor locations (conditions shown in Table 2; one scan = 2 sec, 160° F oil inlet temperature) super-finished baseline design test results.

ing their installation into the gearbox housing (Fig. 6, baseline design).

Test method. The test facility was operated at all conditions at such length to establish steady state conditions. This typically took ~5 min to attain once the first test condition was reached. An example of this will be presented later in this paper. Data taken was stored remotely for playback, if needed. The rate of data acquisition for all tests was 0.5 or 1.0 Hz.

Test gearbox instrumentation. The test facility provided for five operational condition measurements: 1) drive motor power; 2) drive motor speed; 3) test system loop power; 4) lubricant pressure; 5) and all the facility temperatures. Drive motor power to the facility is monitored via a commercially available torque meter. Loop power is measured using a torque-bridge telemetry system attached to the bull gear connect shaft between the test and slave gearboxes. A plethora of thermocouples monitor the lubricant, gearbox housing, bearings, and fling-off temperatures. Fling-off temperatures are found via two different probe types.

Rake and array thermocouple probes were designed and fabricated to indicate the lubricant temperature radially flung off and axially pumped, respectively (Ref. 3). The two different probe types are shown (Fig. 7). The rake probes had five thermocouples across the face width of the gear (six for double-helical design) and the array probe had nine thermocouples in a 25.4-by-25.4-mm (1-by-1-in.) substrate.

Both probes were located very closely to the mesh position of the gears; rake and array probes were located within the test gearbox (Fig. 8).

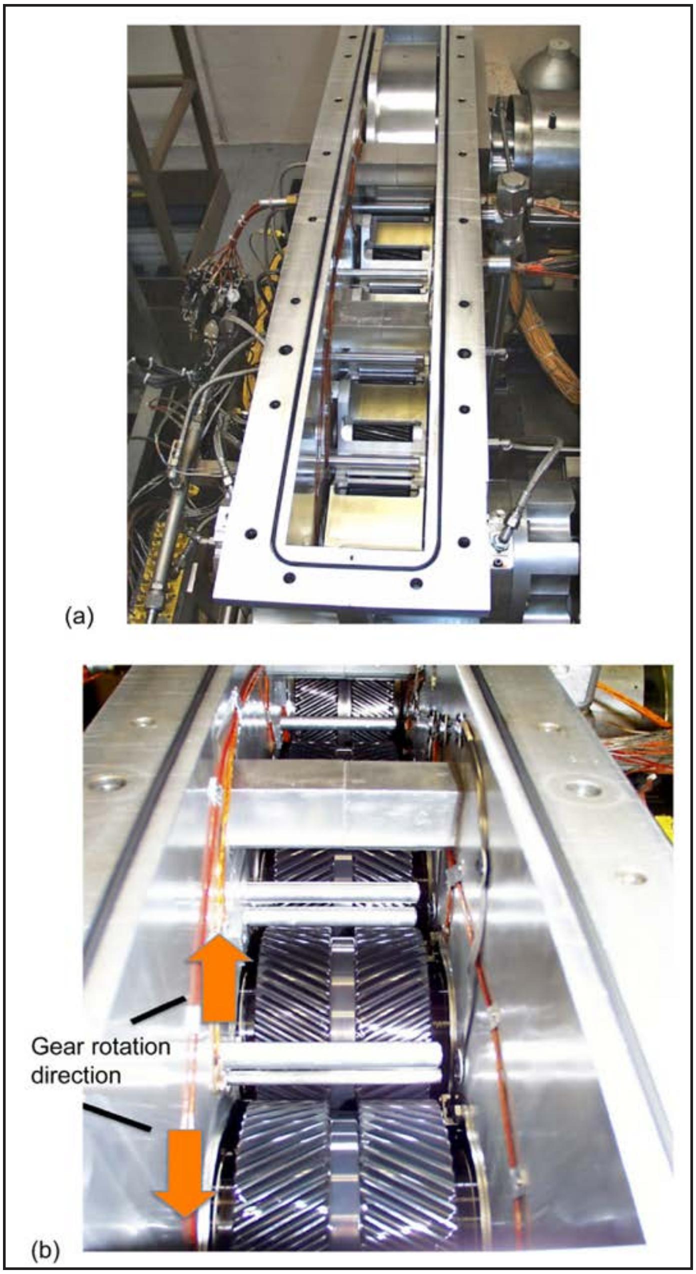

Figure 10 Test gearbox with the shrouding installed and removed — a) shrouding installed (baseline); b) shrouding removed (double-helical inward pumping).

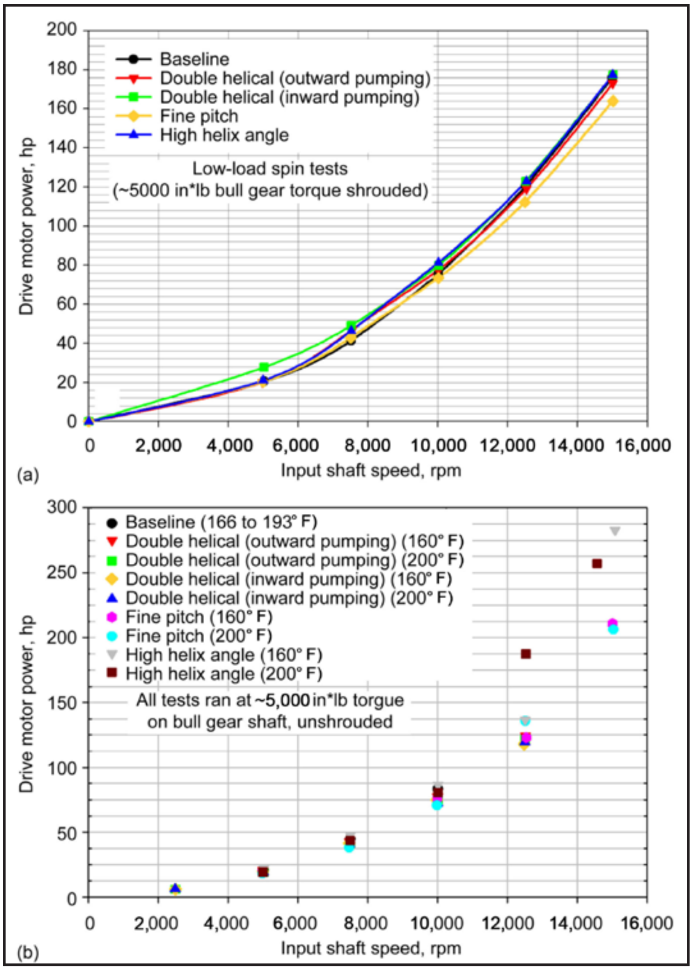

Figure 11 Spin loss data for (a) shrouded and (b) unshrouded conditions.

Table 2 Conditions for Figure 9. Gears were baseline design, superfinished, and 160° F oil inlet temperature

Condition	Input shaft speed (krpm)	Lower power (hp)	Temperature increase across gearbox (° F)	Drive motor power (hp)
A	Warm up			
B	12.5	1,379	50.6	138.0
C	12.5	2,801	55.1	149.2
D	12.5	4,170	59.7	160.1
E	15.0	1,657	73.8	201.9
F	15.0	3,366	79.1	213.2
G	15.0	4,986	83.0	225.1

Test Data

Test operation. Test operation was conducted in the following manner. First the rotational speed and applied load were established and then the temperatures of the facility were allowed to come to steady state, once the oil inlet and outlet temperatures stabilized. An example of a typical time history of a test is shown (Fig. 9) for the conditions given in Table 2 (Ref. 4). In the data to be presented, values from all important variables will be presented at a steady state operating point.

Spin loss data. In order to understand the drive system losses, experimental tests were conducted to full speed (except in some unshrouded cases) at approximately 10% of the full torque of the facility. The data generated was for the various gear designs — with and without shrouding. The test gearbox (top cover removed) with the shrouding installed is shown (Fig. 10(a)) and shrouding removed in (b).

The results from the shrouded and unshrouded tests are shown in Figures 11(a) and (b), respectively. The shrouded gear tests were run at ~160° F lubricant inlet temperature. The unshrouded gear tests were run for most of the gear designs at two lubricant inlet temperatures — ~160 and 200° F.

The non-linear increase in drive motor power requirement for these tests resembles the windage power loss curves generated in Reference 5. The data plotted in all the curves here, and those to come later with respect to "drive motor power," refer to the entire test system (test and slave gearboxes). As shown (Fig. 11(b), for the high helix angle gear design, the facility could not stably run at the 12,500 and 15,000 rpm conditions in the unshrouded case. This is an indication of the windage from the gears interrupting the scavenging of lubri-

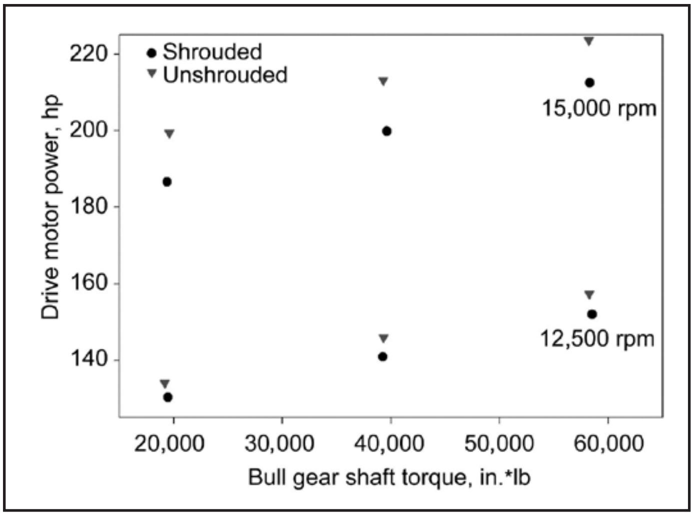

Figure 12 Effect of shrouding on drive motor power. Double-helical gears, outward pumping 200° F oil inlet temperature.

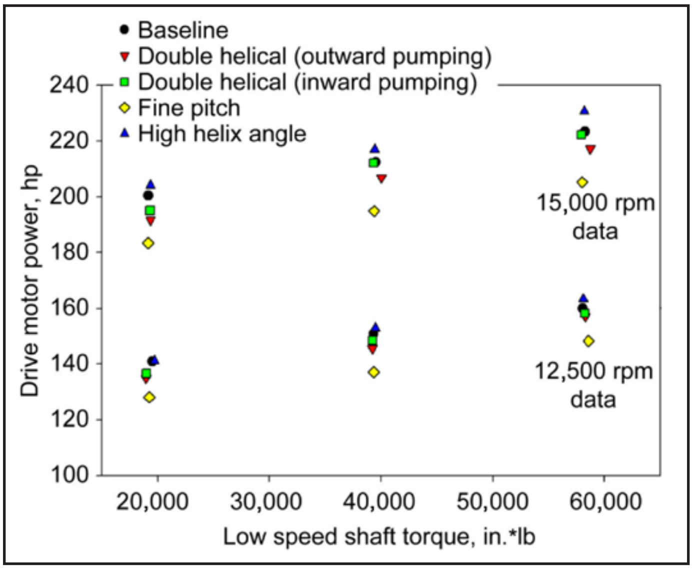

Figure 13 Effect of gear design shrouded on drive motor power, 160° F lubricant inlet temperature.

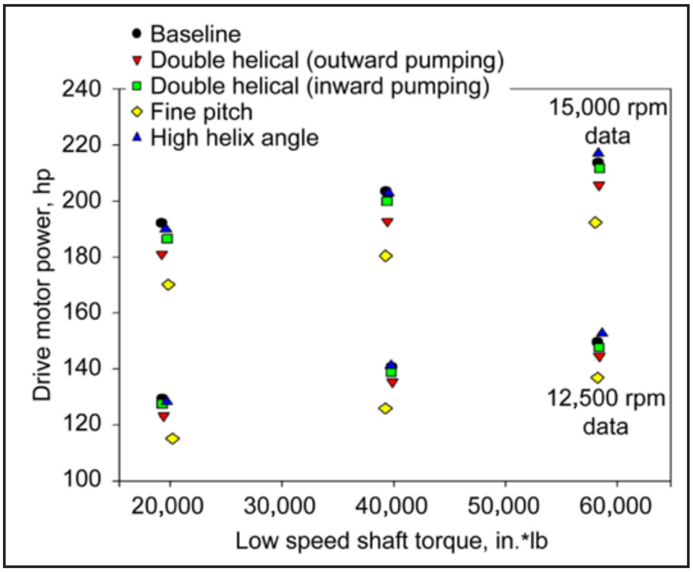

Figure 14 Effect of gear design (shrouded) on drive motor power, 250° F lubricant inlet temperature.

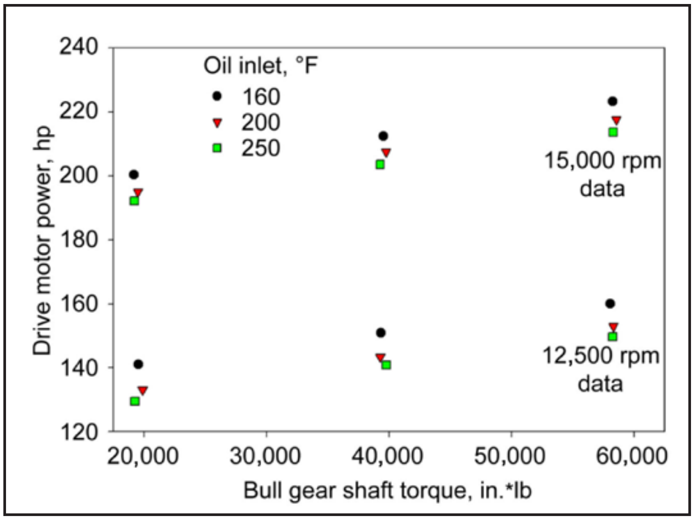

Figure 15 Lubricant inlet temperature effects on drive motor power required (gears shrouded).

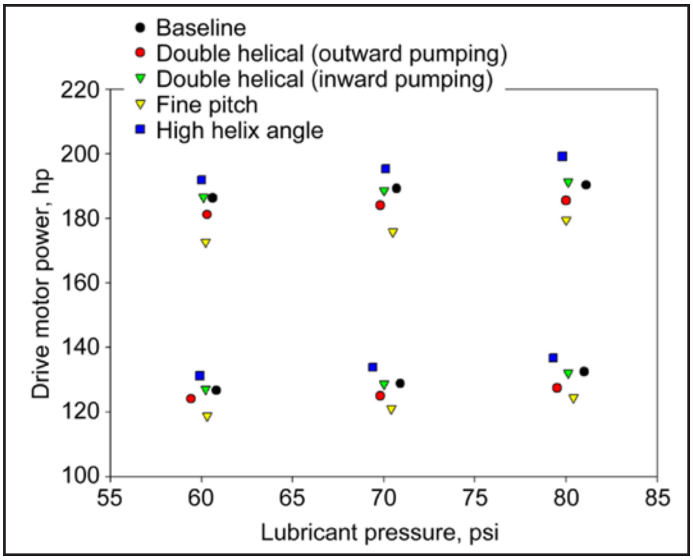

Figure 16 Lubricant pressure effects on drive motor power requirements; shrouded gears, ~19,000 in.*lb torque, 200° F oil inlet temperature.

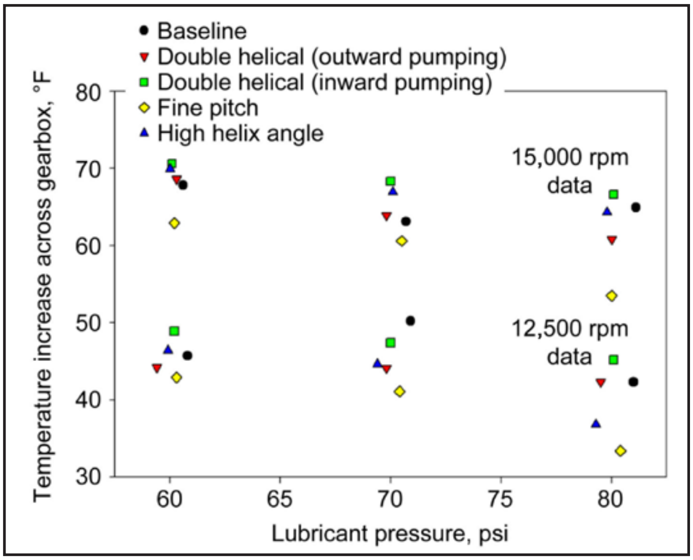

Figure 17 Lubricant pressure effects on temperature increase across the test gearbox, 200° F oil inlet temperature.

cant from the test gearbox.

A comparison of the double-helical — outward pumping design — is shown (Fig. 12). The data indicates the effect of having the shrouds installed. The drive system power requirement difference is a direct measurement of the shroud effectiveness at a given speed and torque combination. Note that rotational speed change is far more important than the level of applied load, meaning that the windage part of the losses is dominating the drive motor power requirements.

Gear design effects. An indication of how the different gear designs affect the performance for the same operating conditions for all four designs is addressed in this section. In Figure 13 the design effect is shown at 160° F lubricant inlet temperature and in Figure 14 at 250° F lubricant inlet temperature as a function of applied bull gear torque at two different rotational speeds. Both figures were for shrouded gears.

It is apparent from these two figures that the rotational speed had the largest effect on the results for a given design. Higher lubricant inlet temperature reduced the power requirement, and the baseline or high helix angle designs produced the largest power requirements. The fine pitch design produced the lowest power requirements for all conditions shown. This result must be tempered by the fact that the test and slave gearboxes had this type of gearing, therefore the power savings of an individual gearbox would be similar to that of the double-helical gear design that were operated in the outward pumping arrangement.

As an example of how the lubricant inlet temperature affects the power loss of a given configuration is shown (Fig. 15). In this figure the drive motor power is plotted vs. bull gear shaft torque for two input shaft speeds for the baseline design. Higher lubricant inlet temperature reduces the power loss of the geartrain at all speed and load conditions. For the baseline design this resulted in a ~10 hp reduction in power loss by increasing the lubricant inlet temperature from 160 – 250° F.

Lubrication jet pressure tests. Three lubricant jet pressure (flow rate) conditions are shown for the two speed conditions and one level of applied load (~33 percent of full torque). The drive motor power required is shown in Figure 16 and the lubricant temperature increase across the gearbox (exit temperature minus inlet temperature) is shown (Fig. 17). In either figure the lower symbol for a given design is the 12,500 rpm data and upper symbol is the 15,000 rpm data. As would be expected, higher flow rate of lubricant reduced the temperature change, but higher jet pressure (flow) increased the power loss for all conditions. The fine pitch design had the lowest drive motor required (note fine pitch gears were installed in both the test and slave gearbox) and minimum temperature increase for any rotational speed or loop torque requirement.

Internal gearbox instrumentation. The final comparison to be made in this paper is how the instrumentation inside the gearbox, and fling-off temperatures, were affected by gear designs and operation conditions. As described earlier, rake probes (radial) and array probes (axially) will be used to generate the data discussed here. The data presented was the maximum from any of the three rake probes or the four array thermocouple sensors. Generally speaking, the highest temperature locations were those at the idler gear positions.

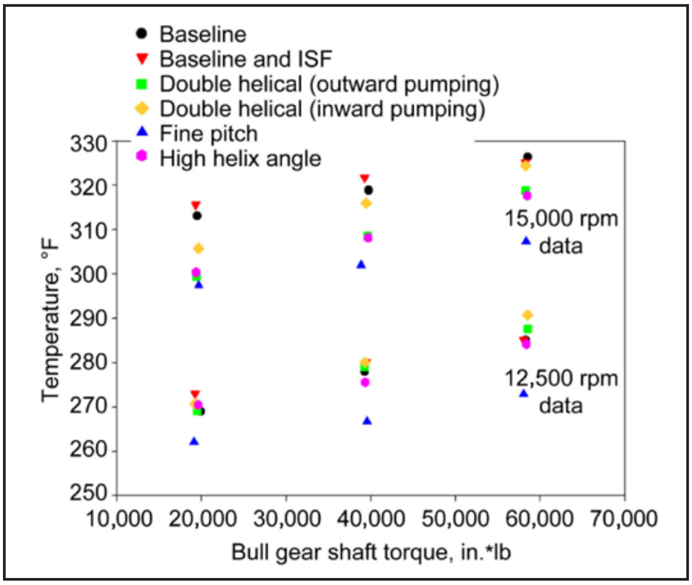

Figure 18 Rake probe lubricant fling-off data, maximum for a given speed and load condition, 200° F oil inlet temperature.

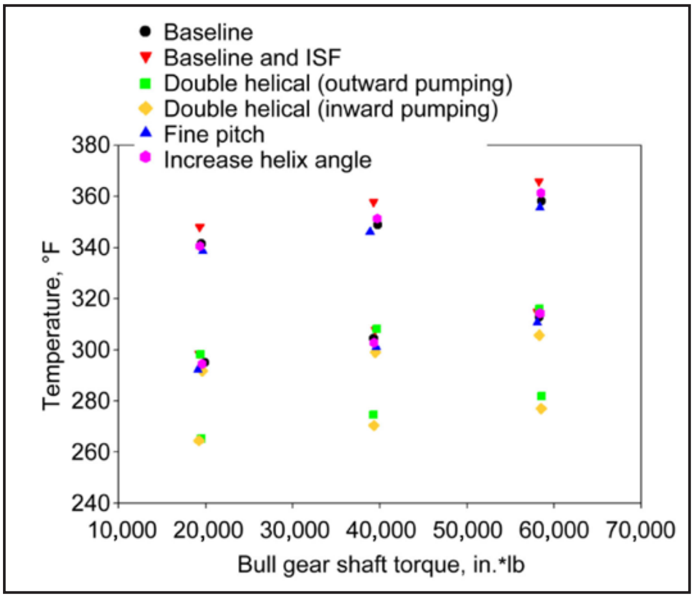

Figure 19 Array probe fling-off data, maximum values for a given speed and load, 200° F oil inlet temperature (Note: Data at higher symbol is at 15,000 rpm, and lower symbol 12,500 rpm).

An example of the rake probe data is shown (Fig. 18); the lubricant inlet temperature for this data was 200° F. Six different test configurations are shown — all with the gears shrouded. As with all the other data presented in this study, the fine pitch gear design performed the best, and rotational speed was a larger factor than applied load on the results. The fling-off temperature from the rake probes could be in excess of 125° F higher than the lubricant inlet temperature.

An example of the array probe data is shown (Fig. 19). This data was also taken at the same inlet lubricant temperatures as the data from Figure 18. This data requires a little more explanation than the rake data. The array probe data is influenced by the axially pumped air-lubricant mixture due to the helical gear meshing action. For the single helical gear designs, the air-lubricant mixture expended from the ends of the teeth impinge directly upon the array sensor. Therefore the single helical gear design data is clustered at a higher temperature than either of the double-helical results. The outward pumping helical gears have approximately one-half of the face width before the air lubricant mixture impinges on the array sensor. The distance that the air-lubricant mixture is pumped in a single helical gear is the complete face width. Therefore single helical results would be expected to have a higher, axially pumped, measured temperature.

Conclusions

Based on the results attained in this study, the following conclusions can be made:

- High-speed gearing benefits from the use of shrouding when the pitch line velocity exceeds ~15,000 ft/min. At conditions above this pitch line speed, the windage losses can dominate those from other sources (gear meshing and bearing losses). Gear design characteristics can also impact the drive system power losses. For the tests conducted in this study, the fine pitch gear design had the least power loss and lowest temperature increase of the lubricant across the gearbox.
- Lubricant inlet temperature changes indicated that higher inlet temperature required less drive motor power for identical conditions for all designs.
- Lubricant jet pressure (flow) affects the power loss and temperature change from inlet to exit of the gearbox. Lower flow resulted in less power required, but resulted in an increase in temperature across the gearbox.
- Special rake and array probes indicated that the temperature of the lubricant that is flung off radially and pumped axially far exceeds the bulk flow temperature exiting the gearbox. The temperature rise can exceed 125° F radially (rake probe), and 165° F axially (array probe) — depending on speed, load and other conditions applied. **PTE**

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Dr. Robert Handschuh has over 30 years of experience with NASA and Department of Defense rotorcraft drive system analysis and experimental methods. He has served as the Drive Systems team leader for the Tribology & Mechanical Components Branch at NASA Glenn Research Center in Cleveland, Ohio for over 15 years, and currently leads the research there in high-speed gearing, including windage, loss-of-lubrication technology, and hybrid gearing. Handschuh is credited with successfully developing many experimental research test facilities at Glenn, and has conducted testing in the following areas: high-temperature, ceramic seal erosion; blade-shroud seal rub; planetary geartrains; spiral bevel gears and face gears; high-speed, helical geartrains; single-tooth-bending fatigue; and high-speed gear windage.

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Ryan T. Ehinger currently serves as Chief Engineer for Bell's V-280 Valor advanced tiltrotor program, and has held previous positions there including Program and Technology Manager for the Bell Helicopter/Army Aviation Applied Technology Directorate (AATD); Future Advanced Rotorcraft Drive System (FARDS) program; and Drive System IPT Lead for the Bell Helicopter/AATD Operations Support and Sustainment Technology (OSST) program. He holds a BS in Mechanical Engineering from Texas A&M, an MS in Engineering Management from Southern Methodist University, and was hired by Bell Helicopter as a Drive System Design Engineer in 2004. Ehinger has authored/coauthored several technical papers, was presented with the American Helicopter Society's François-Xavier Bagnoud award, and holds several U.S. patents related to drive system technology.

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