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Preliminary Investigation of the Thermal Behavior of High-Speed Helical Gear Trains

Robert F. Handschuh
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

Charles J. Kilmain
Bell Helicopter Textron, Inc., Fort Worth, Texas

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Summary

A preliminary experimental investigation of the thermal behavior of high-speed helical gears will be presented. A full-scale torque regenerative test stand has been built to test a representative helical gear train as that used in tiltrotor aircraft. Power loss and temperature data from a wide range of operating conditions were measured. Loop power ranged up to 3730 kW (5000 hp). Drive system components representative of flight quality hardware were used in the test program. The results attained in this initial study indicated that windage losses due to the high rotational speeds that were tested were far more important than the losses due to the gear meshing losses.

Introduction and Background

High speed and heavily loaded gearing are common-place in rotorcraft systems as used in helicopter and tiltrotor transmissions. The components are expected to deliver high power from the gas turbine engines to the high-torque / low-speed rotor reducing the shaft rotational speed in the range of 25:1 to 100:1 (Refs. [1–14]). These components are designed for high power to weight ratio, thus the components are fabricated as light as possible with the best materials and processing to transmit the required torque and carry the resultant loads without compromising the reliability of the drive system. This is a difficult task that is meticulously analyzed and thoroughly tested experimentally prior to being ready for application on a new or redesigned aircraft.

In aerospace designs a combination of different gearing types (spur, helical, and spiral bevel) are needed to successfully connect the engine and rotor systems together. Within the drive system the local combination of shaft speed and torque will dictate the problems that might be encountered to successfully design the system so that all components can surpass the required design life without catastrophic failure. This means that gearing in part of the drive system is operating in close proximity to certain failure modes depending on the location within the drive system.

In most cases the most important and usually the first calculations that are performed are for the bending and contact stress. This may be done using standards such as those developed by the AGMA, ISO, DIN, the finite element method, or a combination of analysis and experiment verification. All manufacturers have a methodology that they utilize and it is typically based on their successes and failures that are part of their company proprietary data obtained by analysis and experiments.

In some designs, however, no data is available internal to the manufacturer or through the open literature and the company is faced with trying to improve the operational behavior of a component or system as the prototype system is under development. The thermal behavior or thermal operational characteristics of a system is one of the areas that is the least understood and has received the least amount of attention in the open literature (Refs. [15–19]). The thermal behavior of a system can cause a success from a bending and contact stress viewpoint into a failure from the resultant thermal operational characteristics (high operational temperatures, gear tooth scoring, and high drive system losses due to the high pitch line velocities).

In certain rotorcraft drive systems, such as that of tiltrotors (see figure 1), a helical gear train was required to orient the engine and rotor centerlines on the aircraft. Therefore the drive system is not only needed to provide the necessary reduction between the engine and rotor, but also has to make the system operate in emergency conditions (Refs. [20,21]) such as one engine inoperative (see figure 2) (Ref. [22]).

Figure 1: Tiltrotor aircraft.

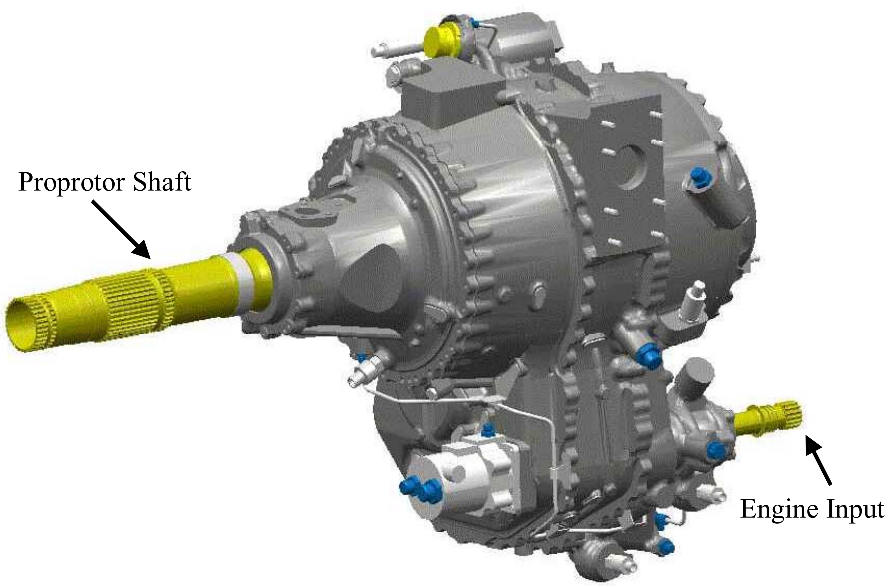

Figure 2: Tiltrotor aircraft drive systems.

Within the gearbox between the engine and the rotor a series of helical gears or a gear train is utilized. This part of the drive system operates at very high rotational speed and carries the full power of the engine during normal operation. Idler gears receive two thermal cycles per revolution as they are driven during one event and become the drivers 180 degrees away when passing the load to the next gear during the second event. Since these gears have two thermal cycles per revolution and due to their extremely light-weight (low thermal capacity) the successful operation of the system in all possible normal and emergency conditions can be difficult.

The objective of this paper is to describe a new high-speed helical drive train facility that utilizes full size, aerospace quality components and the preliminary results attained at nominal operational conditions. The system can operate in the current configuration to 15000 RPM (to simulate the engine input rotational speed) and at power levels to 3730 kW (5000 hp). The facility, components, and initial thermal results will be described.

Test Facility, Test Hardware, Data Acquisition, and Test Procedure

Test Facility: The test facility designed and fabricated for the study of thermal behavior of high-speed helical gear trains is shown in figure 3. The facility is a closed-loop, torque-regenerative testing system. There is a test gearbox and slave gearbox that are basically mirror images of each other. Each gearbox has an input gear, three idlers, and one bull gear. The gearboxes are joined together through the input gears and bull gears via shafting.

Within the slave gearbox there is an additional speed increaser section at the first idler. This is the method through which the drive system is rotated and facility power is provided. In this type of facility only the closed-loop losses (friction losses) are necessary to overcome, therefore a drive motor of considerably less power can drive the entire facility. Also within the slave gearbox is a rotating torque actuator that is used to rotate the bull gear in the slave gearbox relative to the shafting from the test gearbox. This ability to rotate the bull gear relative to the shaft permits adjustable loop torque during operation.

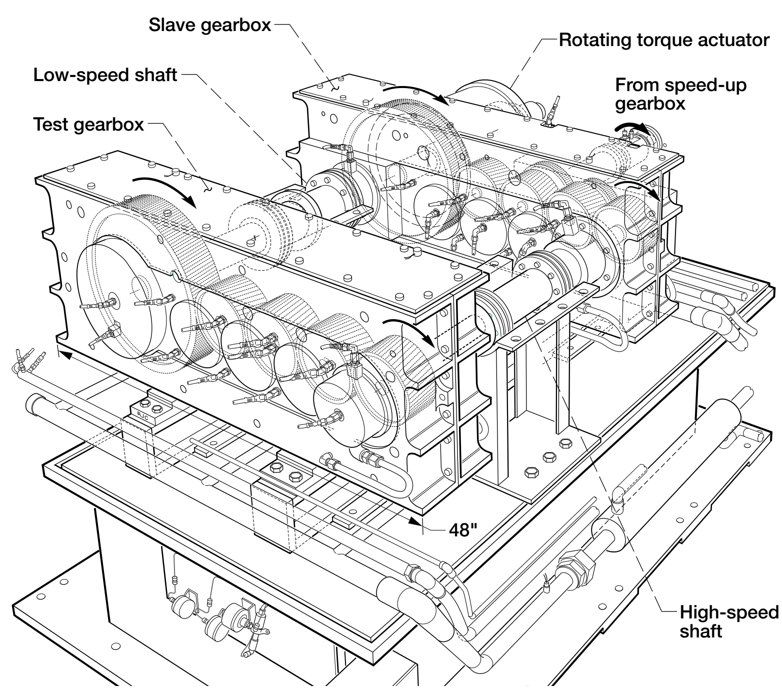

Figure 3: NASA High-Speed Helical Gear Train Test Facility.

The facility is powered by a 373 kW (500 hp) DC drive motor and its output speed is increased using a speed-increasing gearbox. The output of the speed-increasing gearbox then passes through a torque and speed sensor before connecting to the slave gearbox. The entire test stand configuration is shown in figure 4.

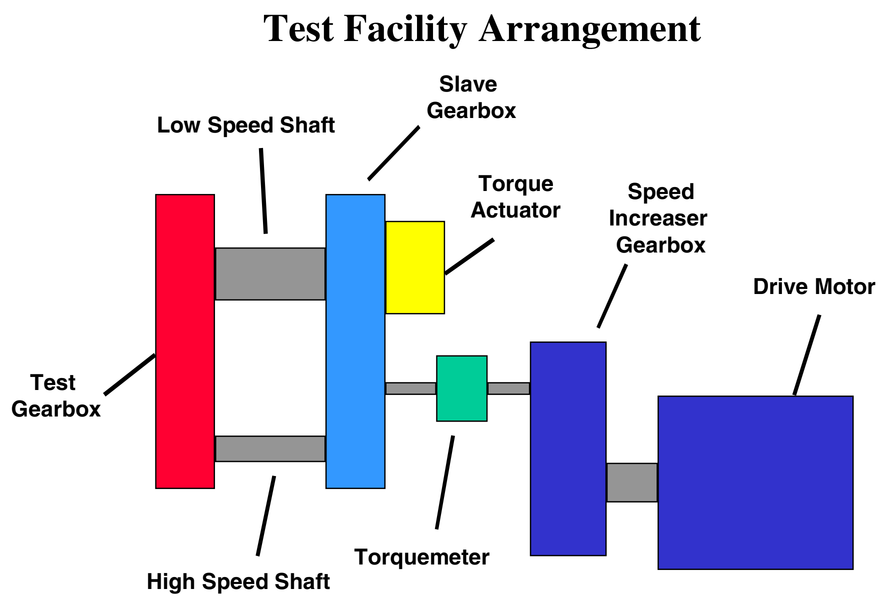

Figure 4: Layout of NASA High-Speed Helical Gear Train Test Facility.

Each gearbox has separate supply and scavenge pumps and reservoirs. Lubrication system flow rate is controlled using the supply pressure. Temperature is controlled via immersion heaters in the reservoir and heat exchangers that cool the lubricant returned from the gearboxes. Each lubrication system has a very fine 3-micron filtration. Nominal flow rate into the test or slave gearboxes at 0.55 MPa (80 psi) is approximately 57 l/min (15 gpm).

The lubricant used in the tests to be described was a synthetic turbine engine lubricant (DoD–PRF–85734). This lubricant is used in gas turbine engines as well as the drive systems for rotorcraft.

Test Hardware: The test hardware used in the tests to be described is aerospace quality hardware. All components are made of the latest high, hot, hardness gear steels and final ground after heat treatment. The basic gear design information is contained in table 1. The input and bull gear shafts have bearings to contain the resultant thrust loads whereas the idler gears only have roller bearings. For the idler gears there is no resultant axial loads due to the thrust force balance. There is however an overturning moment due to the thrust loads that must be carried by the bearing system. A photograph of the test hardware with the gearbox partially disassembled is shown in figure 5. The bearing inner race is integral to the shafts on the idler gears and at other radially-loaded bearings on the input and bull gear shafts. Shrouds for the gears were used to minimize the windage losses that high-speed gear systems possess. Locations where the radial and axial air-oil temperatures were measured using thermocouples from the gear meshes is shown in figure 6.

Table 1: Basic Gear Design Data

Number of teeth Input and 2nd Idler / 1st and 3rd Idler / Bull Gear	50 / 51 / 139
Module (mm), (Diametral Pitch (1 / in.))	3.033 (8.375)
Face Width, mm (in.)	66.7 (2.625)
Helix Angle, deg.	12
Gear Material	Pyrowear EX-53

Figure 5: NASA High-Speed Helical Gear Train Test Facility components.

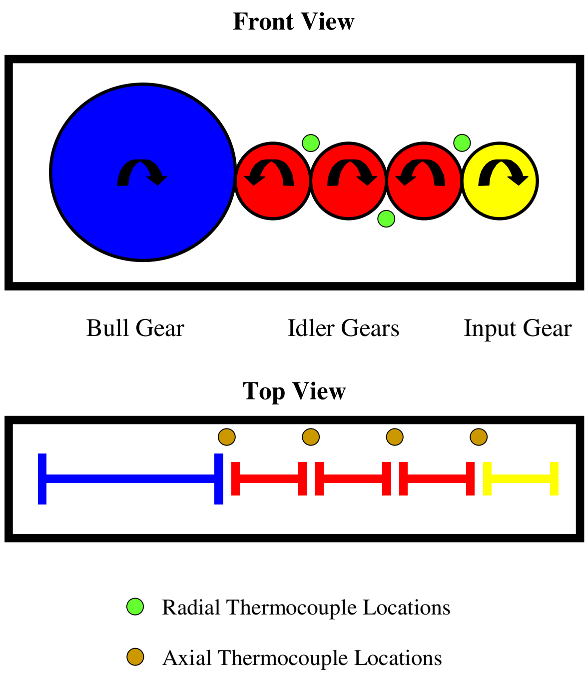

Figure 6: Location and orientation of thermocouples in the test gearbox.

Data Acquisition: The test facility data system monitors three important facility parameters during operation. Speed, torque (supplied torque and loop torque), and temperature measurements were made during all the testing conducted. The measurement for the supplied torque to the facility is accomplished via a commercially available torquemeter. The test system loop torque is measured on the bull gear connect shaft between the test and slave gearboxes. Due to the high-speed and high-torque required at this location, no commercially available system was available. A telemetry system was utilized in this location.

The data recording system used in this study has the capability of taking data from all parameters at a rate of one sample per second. The data is displayed to the test operator in real time. Data is stored in a spreadsheet format and each sensor can be viewed at any time during a test when post processing the results.

Test Procedure: The test procedure that was followed for collecting the data to be presented was the following. For a given set of conditions the facility was operated at those conditions for at least 5 minutes or until the temperatures of interest had stabilized.

Preliminary Test Results

In high-speed gear trains the majority of the losses are found to be due to the resistance of the gears imposed by the air-oil environment within the gearbox. Since the system tested is an aerospace drive system, lubrication is jet fed and scavenged away by separate pumping systems. Also, as mentioned earlier, the gears were shrouded to minimize the interaction of the lubricant and the gear members. Therefore the losses are minimized (not optimized) and the net windage losses for the system should be reasonable. The gears when operating at the highest rotational speed condition approached a very high pitch line velocity of approximately 122 m/s (24,000 ft/min). Most aerospace drive systems try to keep their pitch line velocities below 127 m/s (25,000 ft/min).

Since two nearly identical gearboxes are used for the closed loop system, the resultant drive motor power supplied to the system gives a good representation of the overall system losses from the test and slave gearboxes combined. The slave gearbox had an additional gear mesh, where the drive motor input was connected, along with the rotating torque actuator. Another way of investigating the system performance is achieved through the use of thermocouples in certain locations within the gearbox and lubrication systems. Thermocouple data was taken at axial and radial fling-off locations and at the lubrication system temperature into and out of the gearboxes. The amount of power needed to rotate the gear system is shown in figure 7 for two of the lightly loaded conditions. Input shaft speed was varied over a wide speed range to the maximum and torque was kept nearly constant for the two low levels of torque. Doubling the torque at light load had a minimal effect compared to increasing the rotational speed.

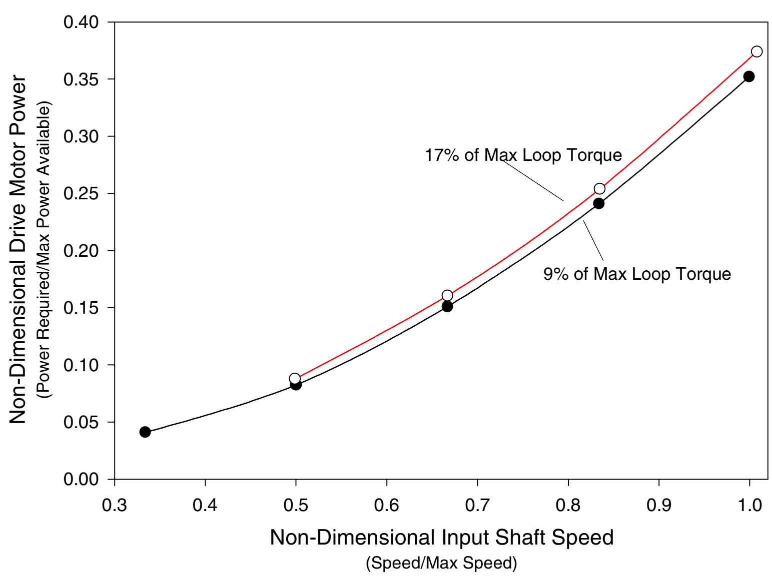

Figure 7: Drive motor power required to rotate entire test—slave gearbox system at two low levels of torque and constant oil inlet temperature.

At the higher speed and load conditions more typical of the rotorcraft in flight, the drive motor power necessary to drive the entire test-slave gearbox system is shown in figure 8. Speed had a very drastic effect on the power required to operate the testing system. The combined effects of speed and load are plotted versus the change in temperature of the lubricant across the gearbox. The results in figure 9 provide similar information of the effect of the two variables on the lubricant temperature increase across the gearbox. From figure 10 the effect of speed is far more important than the level of torque that is applied to the closed loop system.

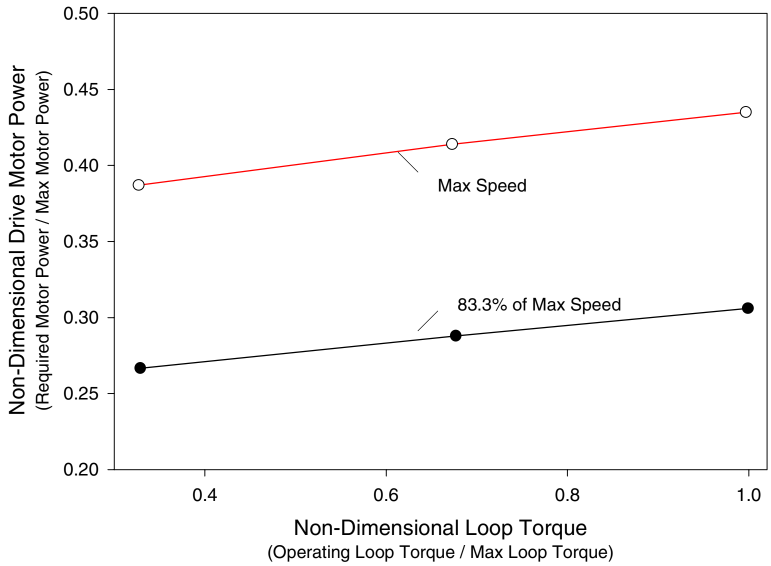

Figure 8: Drive motor power required at high speed and load, at constant oil inlet temperature.

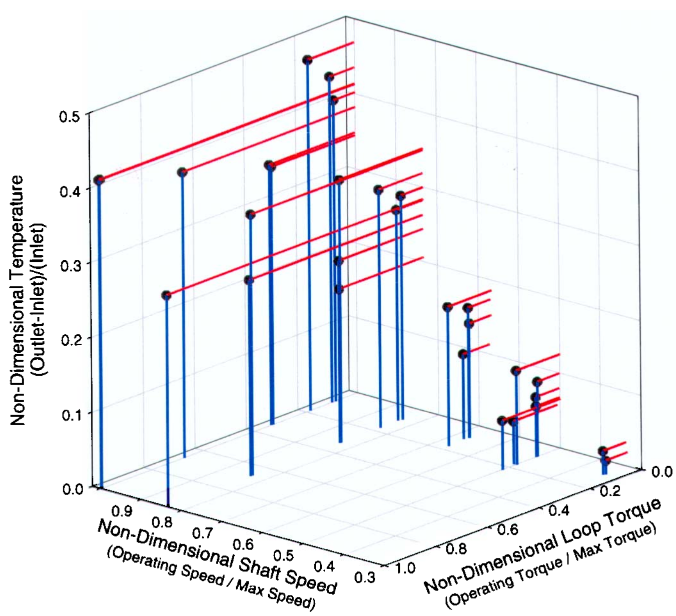

Figure 9: Oil temperature increase across test gearbox at varying shaft speed, load, and oil inlet temperature.

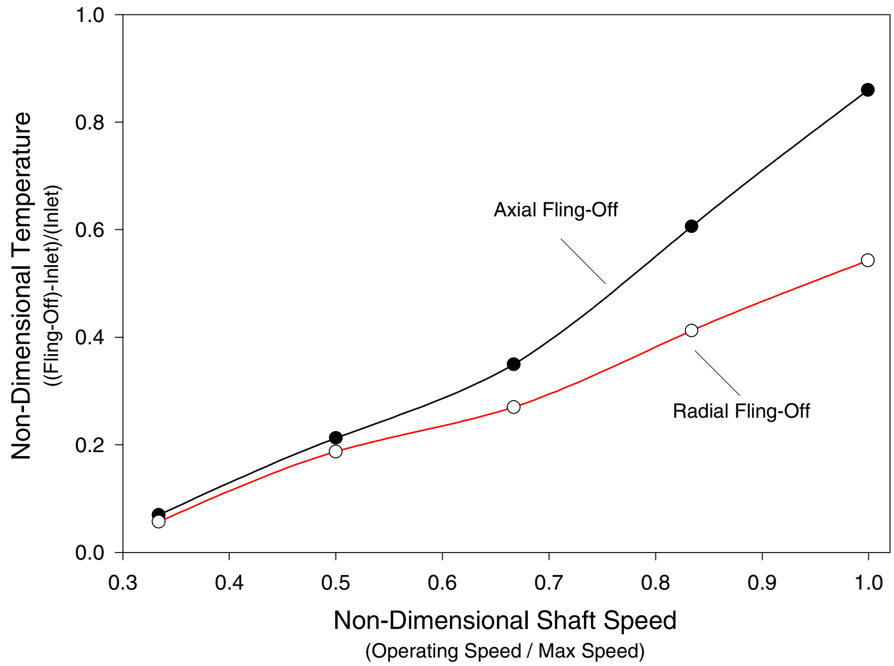

Figure 10: Effect of speed on 2nd-3rd idler gear mesh axial
and radial fling-off temperatures.

Axial - Radial Fling-Off Temperatures: Thermocouples were oriented at the end of meshing axial position between the meshing gears and the radial position at about the half-face width position. This data was taken axially at each meshing exit and at three radial positions as shown in figure 6. For all the data taken in this preliminary study the 2nd and 3rd idler location indicate the highest temperature during all the tests shown in this study. The results from the instrumentation in these locations will now be described.

First the effect of speed on the measuring locations will be described. The data is given as the rise in temperature above the inlet lubricant temperature versus input shaft rotational speed. The results are shown in figure 10 for a wide speed range at light loop load. At low speed the results were nearly the same, but as the rotational speed increased the difference between the two measurement locations became greater. Another comparison can be made at operating conditions that would typically be seen in the operation of the aircraft. Two high-speed conditions over the three high levels of torque in the test system loop are shown in figure 11. As has been shown in all the data that has been presented in this study, shaft rotational speed dominates all other parameters as far as effect on system temperature and losses.

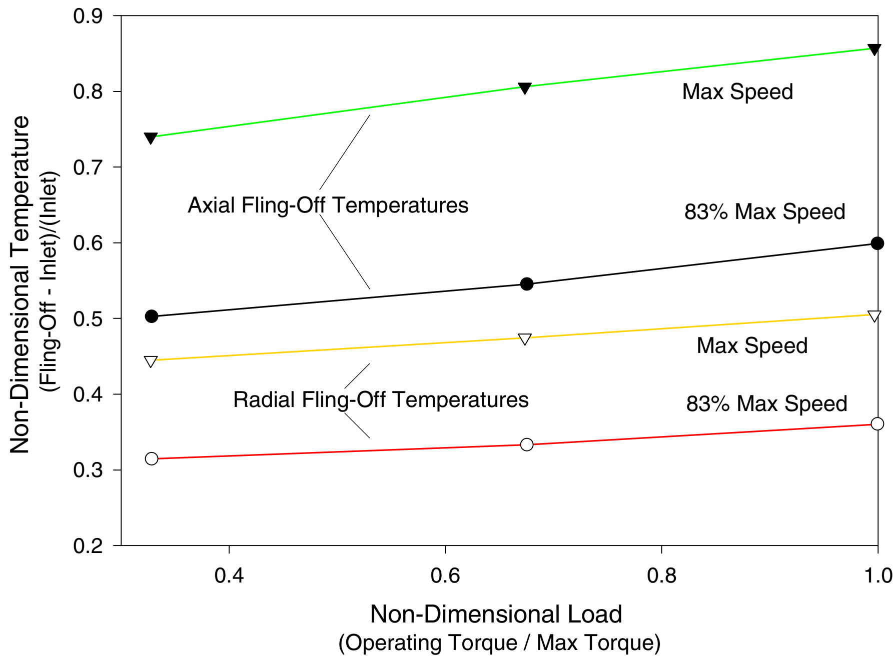

Figure 11: Effect of load on axial and radial fling-off temperature at high speed and load.

Summary and Conclusions

A new facility to empirically investigate the thermal behavior of high-speed helical gear trains has been described. The facility utilizes aerospace-quality components. Tests were conducted at high speed and at varying loads. Using this new capability, a number of steady-state tests were conducted with the following results attained:

1. High shaft speeds resulted in large drive motor power requirements. This effect was also found in the fling-off temperatures measured from the meshing gears and in the lubricant temperature increase from the inlet to exit location of the gearbox.

2. The level of load applied in the torque regenerative loop had an effect that was minor in comparison to that due to high-speed operation.

3. The axial fling-off temperatures measured were greater than the radial fling-off temperatures at all conditions measured.

References

[1] Henry, Z.: Preliminary Design and Analysis of an Advanced Rotorcraft Transmission, American Helicopter Society, AHS Preprint No. 3, November 13–15, 1990.

[2] Bossler, R. and Heath, G: Advanced Rotorcraft Transmission (ART) Program Status, American Helicopter Society, AHS Preprint No. 4, November 13–15, 1990.

[3] Lenski, J.: Boeing Helicopters Advanced Rotorcraft Transmission (ART) Program, American Helicopter Society, AHS Preprint No. 2, November 13–15, 1990.

[4] Kish, J.: Advanced Rotorcraft Transmission (ART) Program Review, American Helicopter Society, AHS Preprint No. 5, November 13–15, 1990.

[5] Drago, R. and Lenski, J.: Advanced Rotorcraft Transmission Program – A Status Report, American Gear Manufacturers Association, FTM–10, 1990.

[6] Krantz, T. and Kish, J.: Advanced Rotorcraft Transmission (ART) Program Summary, NASA TM–105790, AVSCOM TR 92–C–004, July 1992.

[7] Bossler, R. and Heath, G.: Advanced Rotorcraft Transmission Program Summary, AIAA–92–3363, Presented at AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference, July 1992.

[8] Henry, Z.: Advanced Rotorcraft Transmission (ART) – Component Test Results, AIAA–92–3366, Presented at AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference, July 1992.

[9] Bossler, R., Heath, G., and Sheth, V.: Advanced Rotorcraft Transmission (ART) Program Status, American Helicopter Society, Preprint No. 6, Oct. 1993.

[10] Heath, G. and Bossler, R.: Advance Rotorcraft Transmission (ART) Program – Final Report, NASA CR–191057, ARL–CR–14, January 1993.

[11] Kish, J.: Sikorsky Aircraft Advanced Rotorcraft Transmission (ART) Program – Final Report, NASA CR–191079, March 1993.

[12] Krantz, T.: NASA/Army Rotorcraft Transmission Research, A Review of Recent Significant Accomplishments, NASA TM–106508, ARL–MR–138, AHS Forum 50, May 1994.

[13] Lenski, J.: Advanced Rotorcraft Transmission (ART) Program, NASA CR–195461, ARL–CR–224, April 1995.

[14] Henry, Z.: Bell Helicopter Advanced Rotorcraft Transmission (ART) Program, NASA CR–195479, ARL–CR–238, June 1995.

[15] Lewicki, D., Decker, H., and Shimski, J.: Development of a Full-Scale Transmission Testing Procedure to Evaluate Advanced Lubricants, NASA TP–3265, AVSCOM TR 91–C–026, August 1992.

[16] Handschuh, R.: Effect of Lubricant Jet Location on Spiral Bevel Gear Operating Temperatures, NASA TM–105656, AVSCOM TR–91–C–033, September 1992.
[17] Handschuh, R.: Thermal Behavior of Spiral Bevel Gears, NASA TM–106518, ARL–TR–403, January 1995.
[18] Handschuh, R. and Kicher, T.: A Method for Thermal Analysis of Spiral Bevel Gears, Journal of Mechanical Design, Vol. 118, No. 4, December 1996.
[19] Henry, Z. and Stapper, W.: Evaluation of Navy 9cSt Oil in Bell Helicopter M412 HP Gearboxes, NASA/CR—1998-208517, ARL–CR–430, August 1998.
[20] Morales, W. and Handschuh, R.: A Preliminary Study on the Vapor/Mist Phase Lubrication of a Spur Gearbox, NASA/TM—1999-208833, ARL–TR–1912, May 1999.
[21] Handschuh, R. and Morales, W.: Lubrication System Failure Baseline Testing on an Aerospace Quality Gear Mesh, NASA/TM—2000-209954, ARL–TR–2214, May 2000.
[22] Kilmain, C., Murray, R., and Huffman, C.: V-22 Drive System Description and Design Technologies, American Helicopter Society 51st Annual Forum, May 1995.

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