Future Advanced Rotorcraft Drive System (FARDS) Full Scale Gearbox Demonstration

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ABSTRACT

The Future Advanced Rotorcraft Drive System (FARDS) program focused on improving the performance and affordability of current aircraft drive systems. During the course of the program eighteen enabling technologies were developed to achieve these objectives within an existing helicopter transmission system. The transmission system was designed to enhance the Bell 407 light commercial aircraft configuration which has a similar configuration to the OH-58D Kiowa Warrior. Full scale main rotor gearbox testing was completed in 2016, which demonstrated many of these enabling technologies to a Technology Readiness Level (TRL) of 6. The demonstration testing was designed to closely follow the civil certification process (similar to military qualification testing), and included gear tooth pattern development, gear tooth bending fatigue, endurance, and three loss-of-lubrication tests. This testing successfully demonstrated a significant improvement in drive system technologies. The developed technologies are now ready to transition to future rotorcraft, such as Future Vertical Lift.

INTRODUCTION

The Future Advanced Rotorcraft Drive System (FARDS) program was a six-year program focused on eighteen technologies to improve drive system performance and affordability. Each of the eighteen enabling technologies developed under the FARDS program falls within these areas: gears (new materials and processing techniques), bearings (advanced configurations and materials), thermal management (cooling techniques and oil additives), drive shafts (new configurations), and fault detection technologies.

The eighteen technologies include the following:

Gear Technologies

1. C64 gear steel material
2. Cavitation peening
3. Optimized gear teeth geometry
4. Friction welding
5. Hybrid clutch

Bearing Technologies

6. Wave bearings
7. Hybrid Cronidor 30 bearings
8. Fully ceramic bearings
9. Fiber Reinforced Aluminum (FRA) bearing liners

Drive Shaft Technologies

10. Hybrid Mast
11. 3X Supercritical Driveshaft

Thermal Management Technologies

12. Heat pipes
13. Nano-diamond oil

Condition Based Maintenance Technologies

14. Adaptable gearbox monitoring system
15. Fluid quality and debris monitor
16. Non-metallic debris monitor
17. Torsional anomaly detection system
18. Bolt tension detection

As reported elsewhere, some of the FARDS technologies were demonstrated to a TRL6 individually. Examples include the condition based maintenance technologies, specifically the non-metallic debris monitor (Reference 1) and the direct measurement of bolt tension (Reference 2).

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Some of the technologies were integrated into a tail rotor drive shaft TRL 6 demonstration (Reference 3). This paper focuses on the full-scale testing of the technologies identified for the main rotor gearbox (MRGB). The main goal for the FARDS MRGB gearbox demonstration was to evaluate several enhanced design features incorporated into a Bell 407 MRGB. The 407 MRGB is similar to the OH-58D Kiowa Warrior MRGB, but the main difference is that the Bell 407 power rating is 642 HP versus 550 HP for the OH-58D.

FARDS MRGB TECHNOLOGIES

Of the eighteen FARDS technologies, ten were relevant for MRGB demonstrator testing. Of these ten, three technologies were not included in the MRGB demonstrator. The wave bearing technology was excluded due to its longer development schedule, and manufacturing inconsistencies in the hybrid mast technology eliminated its consideration from the demonstration. Lastly, component testing showed that the cavitation peening technology was similar in performance to traditional shot peening, and was therefore excluded.

The seven technologies that made up the demonstrator testing include:

C64 Gear Material

Optimized Gear Teeth Geometry

Friction Welding

Hybrid Cronidor 39 Bearings

Fiber Reinforced Aluminum (FRA) liners

Heat Pipes

Nano-Diamond Oil

In addition to the individual FARDS technologies, an optimization of the MRGB housing and gearbox configuration was performed to accommodate the new FARDS components and to reduce weight. The FARDS gearbox housing was designed to fit within the existing OH-58 and M407 aircraft installation footprint. A cross-section is shown in Figure 1. For this housing design, the formerly separate mid case was incorporated into the main rotor gearbox. The ring gear became scalloped around bolt interfaces, and the entire MRGB case was machined out of a lighter magnesium alloy billet (previously aluminum sand casting) with corrosion protection exterior coating. Bearing re-arrangements and other design changes were also made to the gearbox. Figure 2 displays a cross-section of the modified FARDS MRGB demonstrator. All of the external component attachments, including the mounting pylons, remained the same. The careful redesign made it possible to test the new MRGB in the existing M407 MRGB test stand in the Bell Drive Systems Test lab (DSTL) located at Grand Prairie, Texas. Figure 3 shows the fabricated components involved in the test program.

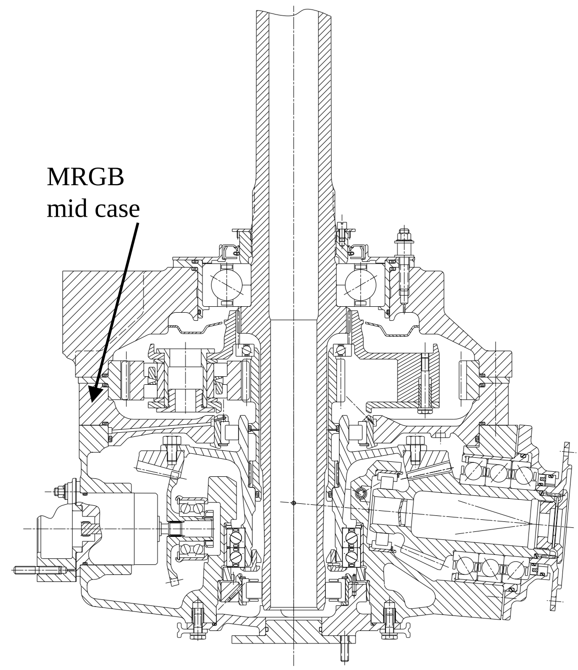


Figure 1. OH-58D MRGB cross-section.

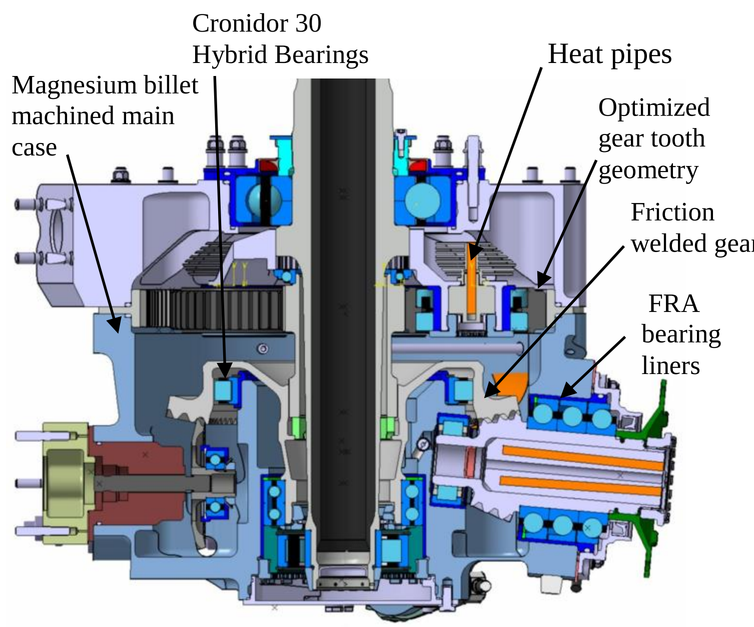


Figure 2. FARDS MRGB demonstrator cross-section.

MRGB DEMONSTRATOR TESTING

The FARDS MRGB development consisted of three phases: design, manufacturing and testing. During the conceptual design phase, an initial look at the technologies and how the improvements impact the gearbox system was performed. The technologies were assessed for both capability and risk, and were integrated into a gearbox layout for the final demonstrator configuration.

Bell Helicopter, with support from outside suppliers and technology development subcontractors, manufactured and assembled the MRGB demonstrator gearboxes. To support the testing, four complete assemblies were fabricated as three test units and one spare. Major components (like gearing) were produced in sufficient quantities to support replacements during fatigue testing and to enable gear tooth pattern development. Two additional gear sets were produced to support loss of lube tests.

The MRGB demonstrator test plan closely followed the civil certification process (similar to military qualification testing) for the entire gearbox. Successful testing of all individual components within the gearbox resulted in a TRL 6 determination of each technology. Tests performed on the demonstrator include:

- Development Bench Test
- Gear tooth bending fatigue test
- Endurance Test
- Loss-of-lubrication test with FARDS MRGB including PEEK bearing cages
- Loss-of-lubrication test with FARDS MRGB including steel bearing cages
- Loss-of-lubrication test with FARDS MRGB including steel bearing cages without heat pipes

MRGB DEVELOPMENT BENCH TEST

The gearbox demonstrator development bench test was conducted in three successive phases. The first phase of testing included: fit and function, oil quality determination, and gearbox test stand shakedown. This phase verified proper operation of the gearbox and lubrication system. The second phase of testing included gear tooth contact pattern development, conducted at full speed and load. Pattern development testing ensures that acceptable load contact patterns exist and that contact area growth with increasing load is within desirable limits. Gear tooth pattern development also includes a comparison of the spiral bevel tooth loading analysis vs. the measured tooth contact pattern under load. Consistency between the two is confirmed in Figure 4. The third phase of testing included thermal testing of the gearbox internal components. These tests concentrated on verifying the performance of the gearbox and lubrication system under extreme conditions and allowed for further evaluation of component performance.

Once all parts were fabricated, the gearbox was assembled, successfully demonstrating fit/function elements. The gear tooth contact pattern development test resulted in acceptable load contact patterns that were within the desired limits when the contact area grew at higher loads. The gears went through testing without any re-grinding of gears during pattern development, showing consistency between the design/analysis and manufacturing of the gears.

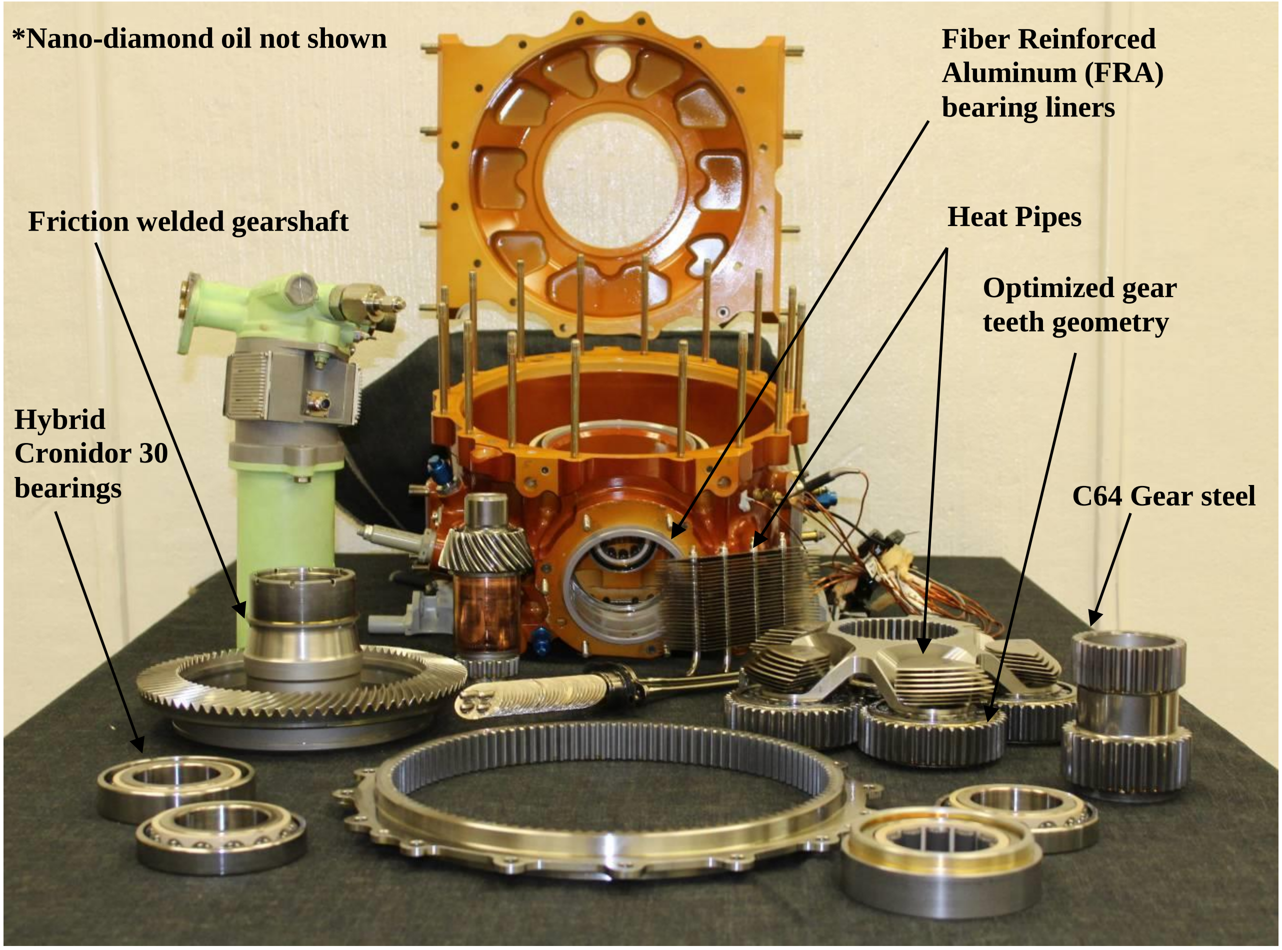
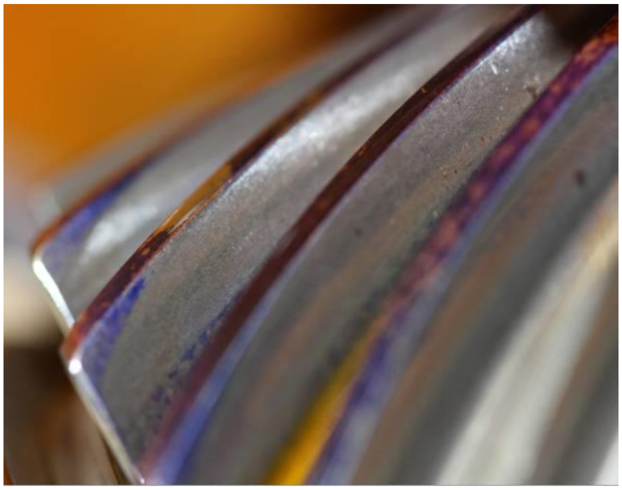


Figure 3. FARDS demonstrator gearbox components.



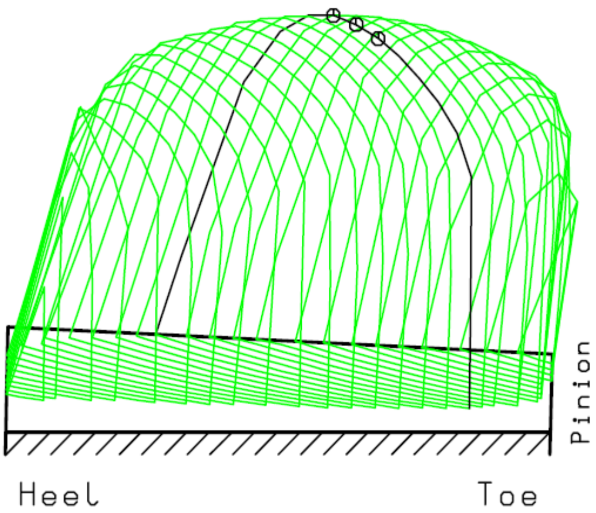


Figure 4. Input pinion gear tooth pattern for full speed and 100% torque.

Boroscope photo left, stress analysis of input pinion, right.

MRGB GEAR TOOTH BENDING FATIGUE (GTBF)

The purpose of the gear tooth bending fatigue test was to substantiate bending fatigue limits for the gear teeth. The FARDS demonstrator gearbox was designed with the assumption that a 20% increase in gear tooth fatigue strength would be available in the test article using C64 gear steel material (over the incumbent gear steel used in the baseline 407 gearbox). Component testing (including single tooth bending fatigue testing) was performed after the gearbox design was finalized, and concluded that the assumption on fatigue strength was not valid. Therefore, the gear tooth fatigue capability of the FARDS demonstrator gearbox was not expected to show an increase in fatigue life or load capacity due to the material change. A gear redesign was not possible due to schedule constraints. To compensate for the lower fatigue capability, a new stair step procedure was developed (see Table 1) to demonstrate actual gearbox capability. The power levels chosen for the load steps are described in Figure 5, where the analyzed gear mesh stress levels were used to drive the load levels in testing.

Table 1. Stair step procedure for gear tooth bending fatigue testing.

Load Step Torque (%)	Component
108%	Achieve 10 million cycles on input spiral bevel pinion
117%	Achieve 10 million cycles on input spiral bevel pinion
140%	Substantiate GTBF for entire gearbox

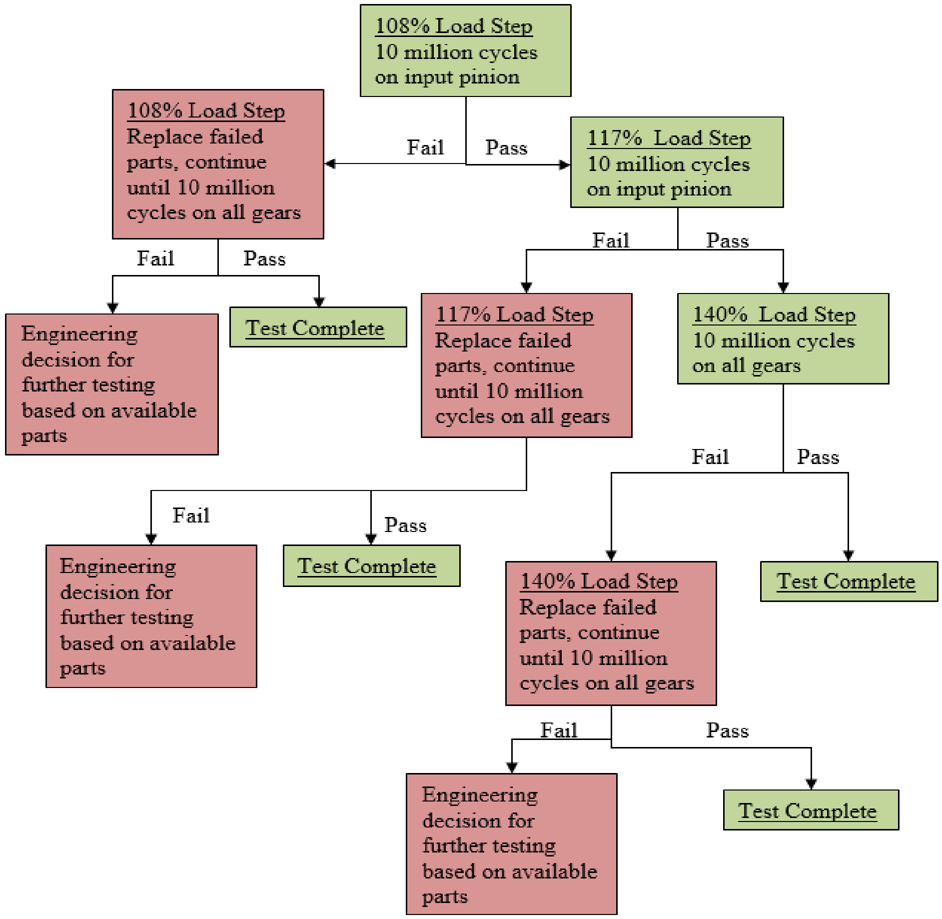


Figure 5. Gear Tooth Bending Fatigue test flowchart.

As indicated at the top of Figure 5, GTBF testing was successfully performed to 10 million cycles for the input pinion operating at 108% test torque. For this element of The gearbox was torn down and all gears were inspected to ensure that no cracks or failures had occurred during testing. The gearbox was built back up to run the 117% test torque element of Figure 5 for the remaining gears. At approximately 95% of the 10 million cycle test, a distinct humming sound emerged from the test stand, just prior to a critical shut down (triggered by the input pinion axial accelerometer). The gearbox was disassembled. Upon borescope inspection, a fracture on two of the input pinon gear teeth was found. Magnetic particle inspection found that none of the remaining gears had cracks and were all in good condition for further testing.

The failure of the input pinion at the test load condition correlates with the component level single tooth bending fatigue test results. With consideration of the remaining inventory of test components, it was agreed that the testing would continue at 117% torque, but the input pinions would be swapped out before 10 million cycles. According to the flow chart, the objective was to complete 10 million cycles at this torque level for the remaining gears. This would enable testing to continue until the longest timed gear would reach 10 million cycles (the planet gears). The input pinion was replaced and testing continued at 117% torque. Accelerometers around the gearbox were analyzed and set up for new limits to catch a failure before damage occurred in the gearbox.

Testing continued for a total of eight input pinion specimens at 117% torque. All eight input pinions incurred some level of damage during fatigue testing. However, pending failures were caught before damage was done to adjacent gears or the gearbox. With no remaining spare input pinions remaining, the test was concluded.

In earlier portions of testing, the input pinions successfully completed 108% torque testing. By swapping out the input pinions, the planet pinions accumulated and ran out the test with 6,600,000 cycles and the remaining test gears completed 10 million cycles at 117% torque. Based on the stress levels calculated for individual gears during testing, material endurance limits were established and are graphically represented in the normalized endurance limit curve shown in Figure 6. This new test method of stair stepping the test load sequence proved to be a good approach for understanding the material limits of the FARDS gearbox.

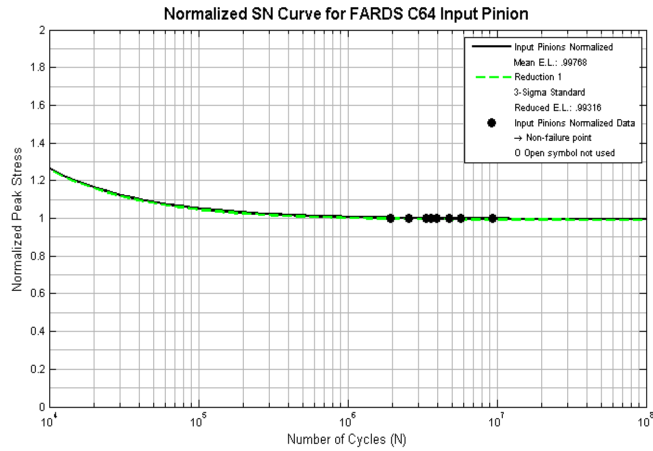


Figure 6. C64 endurance curve from FARDS GTBF testing.

MRGB ENDURANCE TESTING

Previous input pinion test failures of C64 Steel (during the GTBF testing), provided evidence that the original gearbox ratings were too aggressive and risked failure of the gearbox in endurance testing. However, the endurance test was somewhat different from the GTBF test in that endurance testing only utilized a maximum of 100% percent power. The remaining gearbox components were all designed to achieve 140% torque. For these reasons, the plan accepted some risk on the input pinion and continued the gearbox endurance test at the 100% power ratings originally agreed to by the program.

The test plan called for the gearbox to run for a total of 200 hours, but an input pinion failed at approximately 80 hours into the test (approximately 30 million cycles). Post-test evaluation of the input pinion indicated a fatigue failure in the input pinion with the origin of the failure at a subsurface inclusion. The primary fatigue fractured tooth is shown in Figure 7. Inspection of the other test components (apart from the input pinion) showed them to be in working condition with no signs of distress. No remaining spare input pinions were available to continue the test beyond the 80 hours, so endurance testing was stopped at this point. Although the gearbox did not complete endurance testing to 200 hours, it was believed that all the other components would have been able to complete the 200 hours of testing without failure because of the working condition after 80 hours testing (and therefore did not affect the individual TRL levels).

Figure 7. Input pinion failure in the endurance test.

MRGB LOSS-OF-LUBRICATION TESTS

The FARDS program defined three independent loss-of-lubrication (LOL) tests for the MRGB demonstrator. These tests were demonstrating the ability of the transmission to continue operating after loss-of-lubrication. Demonstrating continued operation for at least thirty minutes (following a loss-of-lubrication incident) is the current military rotorcraft gearbox requirement, and was viewed as a baseline for passing TRL 6. Three tests were defined, each one with one variable changed, for comparison of that variable. The three tests were:

- FARDS MRGB assembly using PEEK bearing cages
- FARDS MRGB assembly using steel bearing cages
- FARDS MRGB assembly using steel bearing cages without heat pipes

Test procedures for each configuration were identical in order to ensure valid comparison of the configurations.

LOL with PEEK bearing cages

With the transmission oil pressure stabilized for operating conditions, the oil drain valve was opened allowing the transmission oil to be drained. Transmission oil pressure dropped below five psig in less than two seconds, which served as the starting point of the timer for test purposes. Power levels were set to past similar gearbox test power as the equivalent to minimum flight power. At nearly 10 minutes beyond the 30-minute test time target, an unintended test stand shut down ended the test (due to a high vibration at the MRGB top case radial accelerometer). The transmission was transmitting the designated power at the end of the test.

Upon cool down, the gearbox was inspected in the test stand. The input shaft and the main rotor mast had apparently seized. Disassembly was necessary to inspect gears and bearings. Post-test pictures for comparison are given in Figures 8-12, where the condition of the components within the gearbox immediately after testing are shown. For comparison purposes, similar gearbox post-test pictures are shown for all three loss-of-lubrication tests. Figure 8 shows the FARDS MRGB after the top case has been removed, exposing the condition of the heat pipes and the planetary assembly. With the planetary assembly removed, Figure 9 displays the condition of the gearshaft. It was evident that the PEEK bearing cages were melted within the planetary assembly. During cool-off, the melted PEEK remnants within the box re-hardned around many of the components. Melted PEEK in the gearbox was the reason behind the seized input shaft. Figure 10 shows the bottom of the case with PEEK remnants. The gearshaft roller bearing cage made of PEEK melted. When the gearshaft was removed from the case, the rollers dropped from position, as seen in Figure 11. Magnetic Particle Inspection (MPI) revealed that although the gear teeth were showing signs scuffing and discoloration, they were no signs of surface damage or cracks given the temperatures endured during testing. An example of the input pinion discoloration and scuffing is shown in Figure 12.

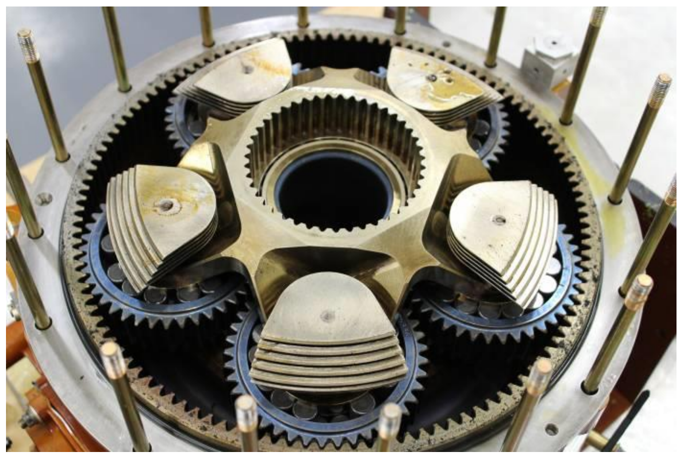


Figure 8. FARDS MRGB LOL with PEEK bearing cages – top case removed.

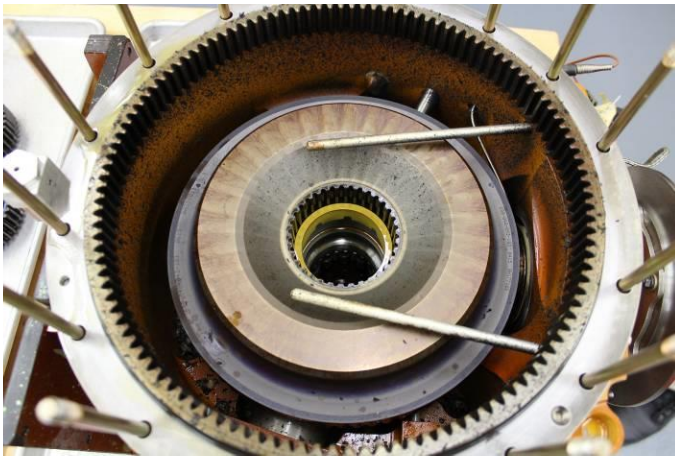


Figure 9. FARDS MRGB LOL with PEEK bearing cages – planetary assembly removed.

Figure 10. FARDS MRGB LOL with PEEK bearing cages – bottom of case.

Figure 11. FARDS MRGB LOL with PEEK bearing cages – gearshaft.

Figure 12. FARDS MRGB LOL with PEEK bearing cages – input pinion.

LOL test with steel bearing cages

With the transmission oil pressure stabilized at the operating power, the next loss-of-lubrication test was repeated for the gearbox with steel bearing cages. This time, after testing ran approximately 73 minutes, the temperature rise observed at the spiral bevel gear-mesh fling-off began increasing at a rate to indicate failure was imminent. To prevent cascading failures and to preserve evidence of the initial failure mode, it was decided to shut down the test. After cool down, the input gear was free to turn in the test stand. After teardown, the gears and bearings were in good condition. Post-test pictures in Figures 13-17 show the condition of the components within the gearbox immediately after testing. Figure 13 shows the FARDS MRGB after the top case has been removed, exposing the condition of the heat pipes and the planetary assembly. Both the heat pipes and the planetary did not show signs of distress. With the planetary assembly removed, Figure 14 displays the condition of the gearshaft, which also showed no sign of distress. Figure 15 shows internal case discoloration due to heat during testing. Figures 16 and 17 show the input pinion with moderate scuffing. The scuffing found on the gear teeth show explains the temperature rise found during testing.

Although both the PEEK and steel bearing cage configurations lasted beyond the 30 minute recommended loss-of-lubrication test time, inspection showed that many of the PEEK bearing cages had signs of melting. This melting proved to be the failure mode during the test. In contrast, the LOL test with steel cages remained in place after the test.

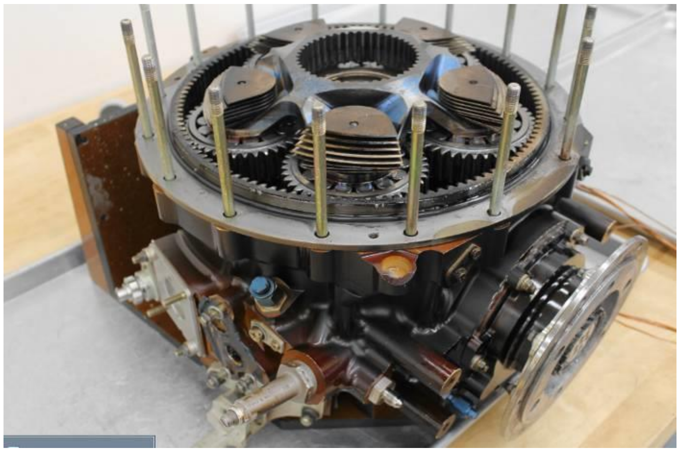


Figure 13. FARDS MRGB LOL with steel bearing cages – top case removed.

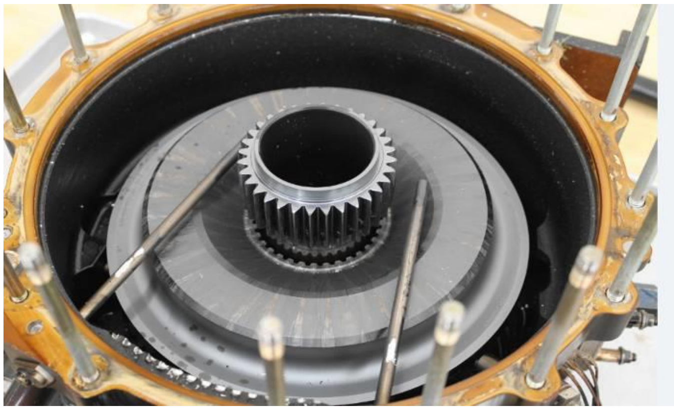


Figure 14. FARDS MRGB LOL with steel bearing cages – planetary assembly removed.

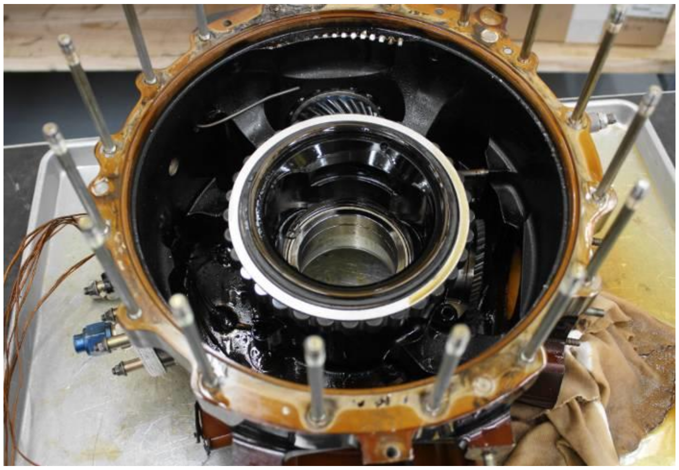


Figure 15. FARDS MRGB LOL with steel bearing cages – bottom of case.

Figure 16. FARDS MRGB LOL with steel bearing cages – gearshaft.

Figure 17. FARDS MRGB LOL with steel bearing cages – input pinion.

LOL test with Steel Cages excluding Heat Pipes

The final loss of lube test evaluated the gearbox with steel bearing cages and eliminated the heat pipes. After approximately 85 minutes of testing, similar to the previous LOL test, the temperatures observed from the spiral bevel gear-mesh fling-off were increasing at a faster rate to indicate imminent failure. The test stand was shut down. Figures 18-22 show the condition of the components within the gearbox immediately after testing. Figure 18 shows the FARDS MRGB after the top case has been removed, exposing the condition of the heat pipes and the planetary assembly. With the planetary assembly removed, Figure 19 displays the condition of the gearshaft. Figure 20 shows internal case discoloration due to heat during testing. Figure 22 show scuffing on the input pinion gear teeth.

Although the tests with and without the heat pipes showed no improvement for the heat pipes, both tests lasted well beyond current equivalent times. Some consideration for the heat pipes were evaluated, however not in too much depth because of the success of both test times.

Figure 18. FARDS MRGB LOL without heat pipes and steel bearing cages – top case removed.

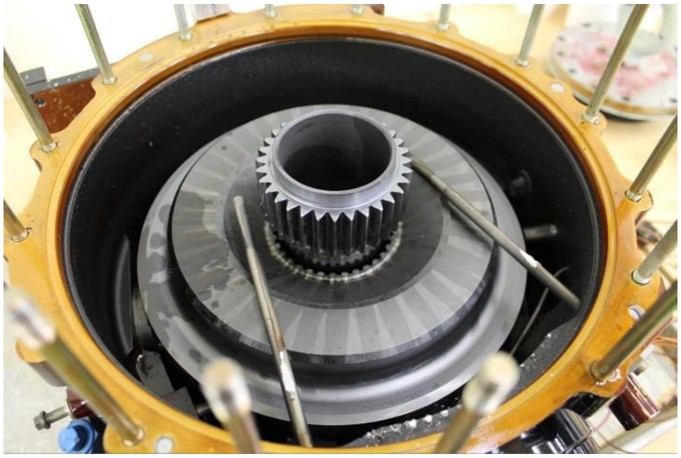


Figure 19. FARDS MRGB LOL without heat pipes and steel bearing cages – planetary assembly removed.

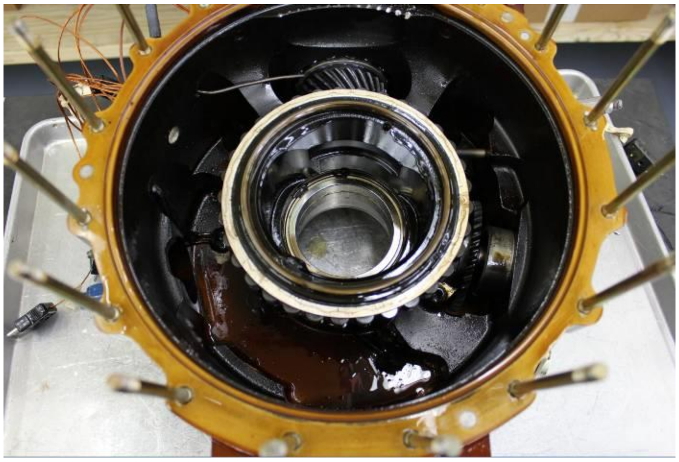


Figure 20. FARDS MRGB LOL without heat pipes and steel bearing cages – bottom of case.

Figure 21. FARDS MRGB LOL without heat pipes and steel bearing cages – gearshaft.

Figure 22. FARDS MRGB LOL without heat pipes and steel bearing cages – input pinon.

In summary, all three gearbox test configurations met or exceeded the current 30-minute loss-of-lubrication requirement. Although the PEEK configuration was the shortest test run, it still successfully sustained test operation for thirty minutes. Both steel cage configurations (with and without heat pipes) endured testing over twice the test goal time.

CONCLUSIONS

The FARDS MRGB testing successfully integrated and demonstrated seven technologies to a TRL 6. Gearbox bench testing showed that the gearbox functioned properly during full load and high temperature conditions. Development testing within bench testing also demonstrated the validity of the analysis tools used for the program, as no additional gear tooth regrinding was required after pattern development testing. The FARDS MRGB gear tooth bending fatigue test and endurance test demonstrated that full scale test results agreed with component test results, further establishing endurance limits for C64 material. The loss-of-lubrication testing successfully demonstrated that the gearbox could exceed the 30-minute loss of lubrication requirement.

Overall, the program reiterated the fact that research and development is a learning environment. Although testing saw failures, much more learning was achieved by setting stretch goals. After the successful TRL 6 MRGB testing, and other TRL 6 tests, the FARDS technologies are considered ready for transition. These technologies are applicable to current rotorcraft (civilian and military), and future rotorcraft, such as Future Vertical Lift.

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