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US Army Research Laboratory

UH-60L Main Module System Checkout for the Vehicle Innovative Powertrain Experimental Research Facility

by Mark R Riggs, Hemant S Suthar, and Brian D Dykas

NOTICES

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Vehicle Technology Directorate, ARL

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14. ABSTRACT

The US Army Research Laboratory is procuring a transmission research facility for the validation of drivetrain component technologies in a laboratory environment. The Vehicle Innovative Powertrain Experimental Research (VIPER) facility will provide a versatile 2,000-hp class transmission testbed with dual-input capability and two-output capability representative of Army vertical lift and other vehicle platforms. The drive-system main module from the UH-60L Black Hawk helicopter was selected as the commissioning test article and initial research specimen because of its ability to transmit the VIPER facility's highest power output in a dual-input and two-output configuration. Modifications were made to the UH-60L main module's input interface and oil-cooling system, allowing it to be tested in the laboratory environment described herein. A system checkout test of the commissioning test article was performed and described to ensure the modifications function as designed and verify the commissioning test article is fit for service in this environment. This report describes early characterization of the main module for use in the VIPER facility, including some operational and configuration considerations specific to the test-stand environment. Baseline operating data from these experiments are also provided.

15. SUBJECT TERMS
UH-60, Black Hawk, transmission, VIPER, Vehicle Innovative Powertrain Experimental Research, checkout

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1. Introduction and Background

The US Army Research Laboratory (ARL) conducts research in drivetrain technology for military vehicles, most notably in aviation platforms such as helicopters. This research has led to improvements in helicopter drivetrains, such as in the AH-64E Apache Guardian. The Apache Guardian's rated power was upgraded from 2,828 hp to 3,400 hp with little impact to the transmission weight and volume partially because of face gear technology developed in collaboration with ARL (ARL News 2012). Along with other weight-saving technologies, the Apache Guardian drivetrain has a 26% increase in power density compared with the Apache Longbow drivetrain (Gilbert et al. 2008). To enable more rapid transition of technologies such as this, ARL has determined that a dedicated research stand is needed to simulate system-level drivetrain environments for vertical takeoff and landing (VTOL) configurations and loading conditions. The Vehicle Innovative Powertrain Experimental Research (VIPER) testbed will provide this capability for a wide variety of VTOL platforms through motors capable of simulating platform-specific speeds and loads, with modularity of design to accommodate platform-specific configurations.

To imitate the conditions experienced by the transmission on a helicopter, two AC electric motors are used as inputs simulating the power normally delivered by gas turbine engines and two additional four-quadrant AC motors absorb power simulating the main rotor mast output and tail rotor takeoff output. The two inputs are identical 1,000-hp motors with speed-increasing gearboxes capable of 10,000 rpm shaft speeds driving the transmission's high-speed input. The main rotor (mast) output is simulated with a 2,000-hp motor geared down to a maximum speed of 508 rpm. The tail rotor loads are absorbed with a 250-hp motor capable of 6,000 rpm directly connected to the transmission tail takeoff. Mast loads and moments that would be reacted within an aircraft due to steady and maneuver forces at the mast are applied through a swashplate assembly outfitted with hydraulic load actuators. The swashplate loading assembly has 5° of freedom to simulate loads in the X, Y, and Z directions as well as pitch and roll moments. The VIPER facility's layout is shown in Fig. 1, and additional motor performance-envelope information is given in Appendix A.

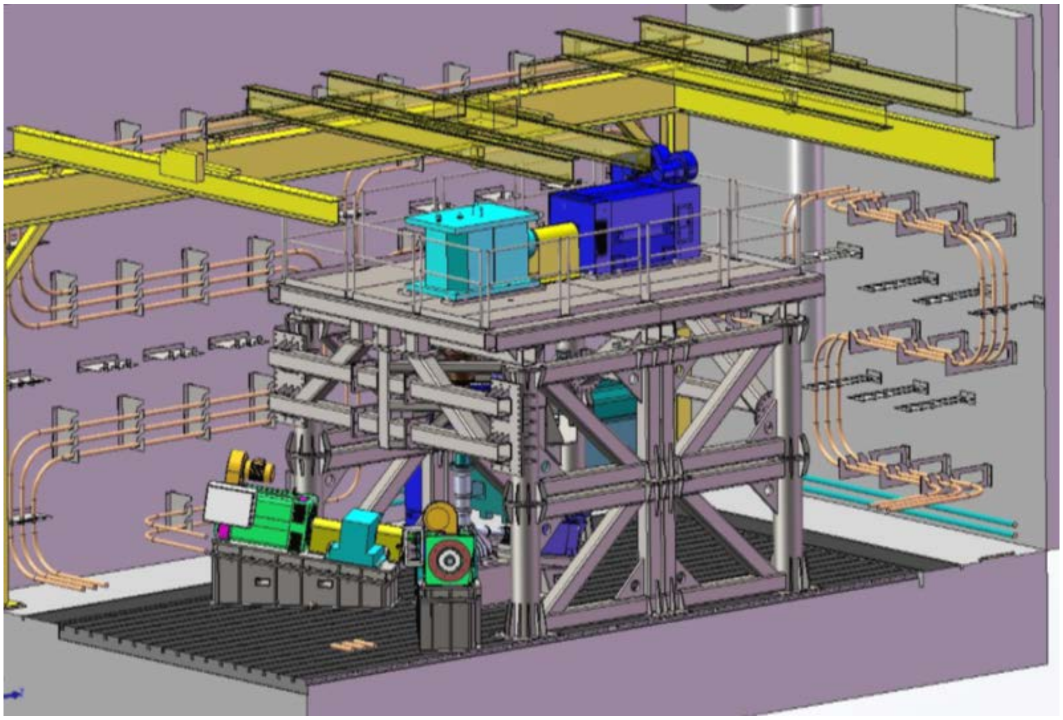
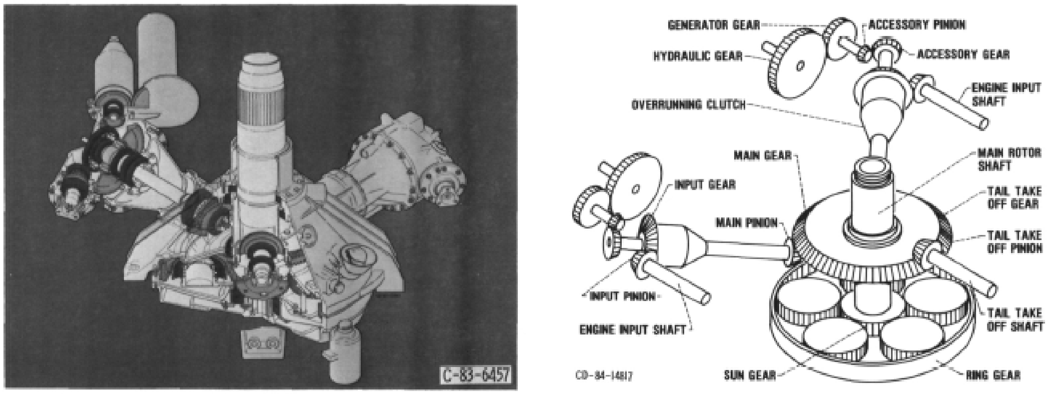


Fig. 1 VIPER test-stand design

The VIPER test stand will provide a transition path for promising subscale vertical-lift technologies currently under study within ARL. As described during the 2018 American Helicopter Society conference (Berkebile et al. 2018), ARL research to improve performance of rotorcraft drives under loss-of-lubrication conditions culminated in the test of a full gearbox after several years of subscale screening experiments. The system-level study revealed unexpected behavior unattainable from coupon- and component-level studies. Along with loss-of-lubrication technologies, hybrid gears have been an area of successful research within ARL with static and dynamic bull gear tests reaching up to 3,300 hp; however, they have yet to be demonstrated in a full transmission configuration (LaBerge et al. 2016). Hybrid gears are an interest to ARL because it is a weight-saving technology accomplished by substituting the steel web of a gear with a lightweight carbon-fiber composite material. The ability to increase specific power through lighter gears is especially advantageous when considering the potential weight penalty introduced by multispeed rotorcraft transmissions. Multispeed rotorcraft transmissions aim to increase the overall efficiency of a helicopter through drivetrain speed changes of up to 50% (Stevens et al. 2015). While increased efficiency through a multispeed transmission is desired, it also presents added complexity for the analysis of health-monitoring systems. Vibration signatures of single-speed and multispeed transmissions will be studied analytically through the development of a finite element–contact-mechanics model similar to a research effort focused on the OH-58 Kiowa’s planetary system (Cooley and Hood 2018). Analytical models will be validated through experimental analysis conducted with the VIPER test stand. Before the VIPER test stand can support these technologies it needs to be characterized through a commissioning test article. The characterization will validate operating procedures, record the test-stand behavior under experimental conditions, and reduce the risk of damage to valuable research test articles. A robust commissioning test article is needed for this initial study.

The main module of the UH-60L/M transmission was chosen as the commissioning test article because of its ability to transmit power exceeding that of the test stand, configuration representative of many twin-turbine helicopters, research topics relevant to the Army’s current fleet, and availability of hardware and spares no longer rated for flight. The UH-60 transmission is relevant to both the current and future force of the Army as the UH-60M Black Hawk helicopter aligns with the Army’s Modernization Strategy and continues to be acquired by the Army (DAMIR 2016), with similar variants in service with other Department of Defense services. The UH-60L/M is able to transmit over 3,400 hp continuously, well exceeding the VIPER facility’s maximum continuous power rating of 2,000 hp at the mast. The UH-60L/M main module also provides a transmission configuration that will test the VIPER facility’s ability to coordinate two motor inputs with two motor outputs. Although the VIPER facility will be capable of running a single-input helicopter transmission and a variety of other drivetrain configurations, this test article allows the test stand to be commissioned at full capacity with all motors simultaneously in the dual-input and two-output configuration.

This main module is the core of the UH-60 transmission, transmitting power from the input modules to the main rotor mast and the tail takeoff shaft. The input modules transmit power through a splined quill shaft to the main module input bevel gears. This bevel gear is connected to a sun gear in a final-stage planetary reduction, with the main rotor driven by the planetary carrier. A bevel gear on the main gear drives the tail takeoff pinion. Figure 2 shows the overall gearing configuration of the UH-60 transmission, including the connection between the input modules and the main module (Weden and Coy 1984).



(a) Detail. (b) Schematic.

Fig. 2 UH-60 main transmission gear configuration: a) detail and b) schematic (reprinted from Weden and Coy 1984)

2. Methods

2.1 UH-60L Main Module Hardware Modifications

To match the initial VIPER research-stand configuration, a UH-60L main module was operated without the input modules, and an auxiliary oil-cooling system replaced the oil cooler found in the aircraft. This auxiliary oil-conditioning system was used in place of the tailshaft-driven oil cooler from the aircraft to allow for independent control of oil conditioning and permit operation of the transmission at speeds other than the single design speed at which it operates on the helicopter. Custom input adapters, shown in Figs. 3 and 4, sealed the input module's mating face while providing a bearing supported shaft to drive the main module's bevel gears. The outward-facing input adapter shaft served as a mounting point for custom flanges and couplings. Figure 4 shows the main module with input adapters and custom flanges.

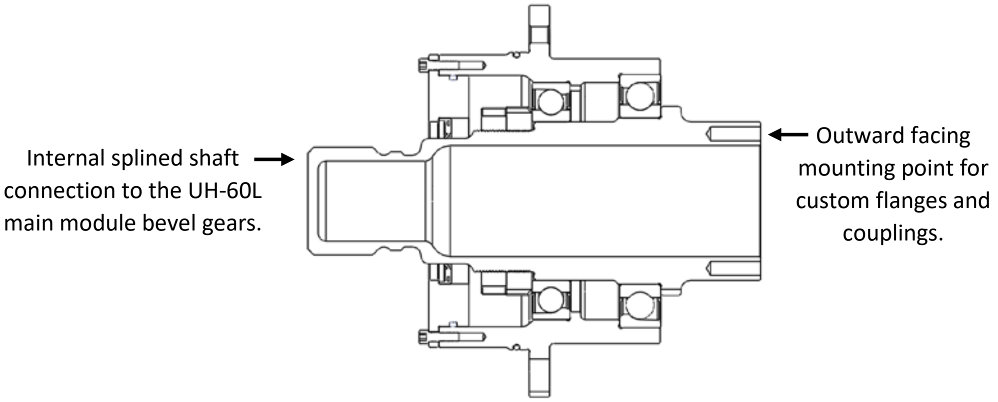


Fig. 3 The input adapter is a bearing supported shaft with a splined interface to seal the UH-60L main module

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Fig. 4 UH-60L transmission main module with input adapters and custom flanges

The auxiliary oil-conditioning system was mounted on a cart along with control and signal conditioning hardware for the test article instrumentation. Oil was pumped by the transmission's internal oil pump to this auxiliary oil-conditioning system. A brazed plate oil-to-water heat exchanger sized to absorb 200 hp of waste heat provided heat rejection to an external process chilled water (PCHW) system. When the transmission oil temperature was less than 160 °F, it bypassed this heat exchanger through a thermal bypass valve, mimicking the bypass scheme in the oil-cooler circuit within the aircraft. When the oil temperature was above the threshold, it was redirected through the heat exchanger to be cooled. A proportional valve in the PCHW loop controlled the cooling-water flow rate. The heat exchanger was connected to the building PCHW system with an average pressure of 25 psi and an approximate available flow rate of 100 gal/min. Figure 5 shows the oil-conditioning system on the auxiliary cart.

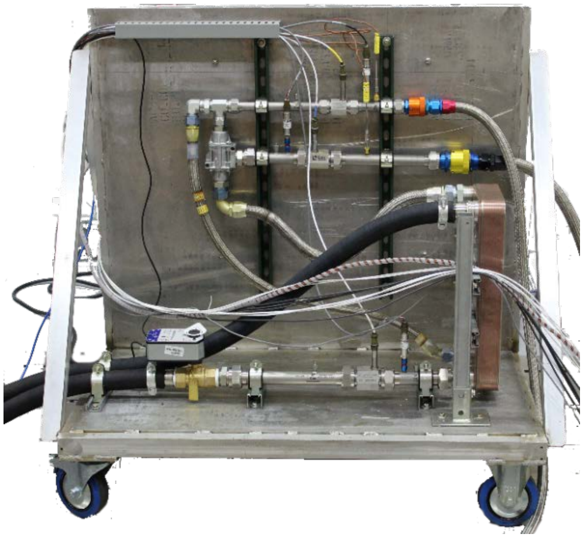

Fig. 5 Oil-cooling cart

2.2 Experimental Configuration and Instrumentation

The main module was mounted to a support stand at the same mounting locations as used in the aircraft, and this stand was secured to the floor. One input adapter was connected to a 20 hp motor capable of 3,600 rpm through a 3.06:1 gear ratio speed-increasing gearbox, and the second input was allowed to freewheel as shown in Fig. 6. The UH-60L main module oil input and output ports were connected to the oil-cooling cart and the input adapter oil ports were directly connected to the transmission sump. The transmission was instrumented with resistance temperature devices (RTDs), thermocouples, accelerometers, temperature switches, and chip detectors according to Figs. 7 and 8. The auxiliary cooling cart was instrumented with flow meters, pressure transducers, thermocouples, and RTDs as annotated in a diagram of the cooling circuit shown in Fig. 9.

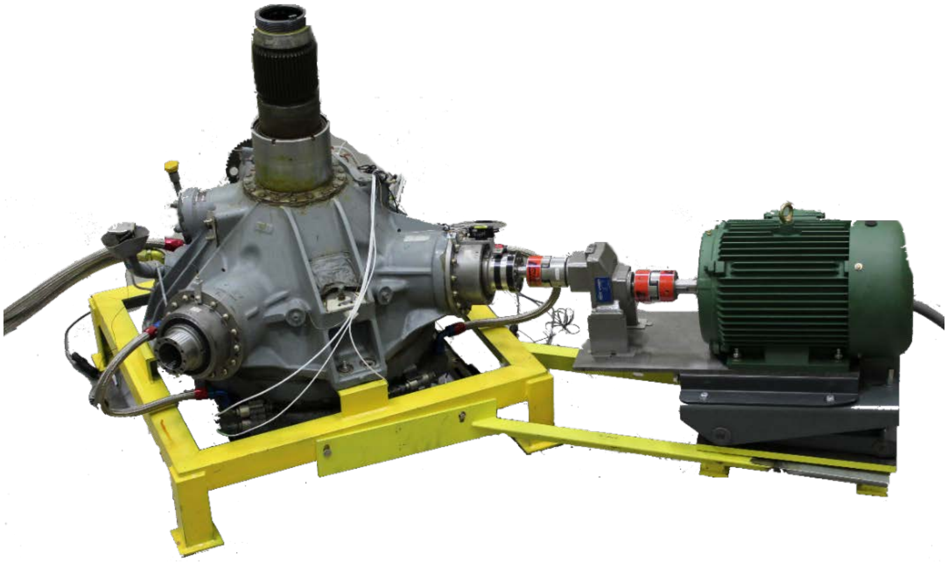

Fig. 6 UH-60L main module test setup with a geared motor input, forward side

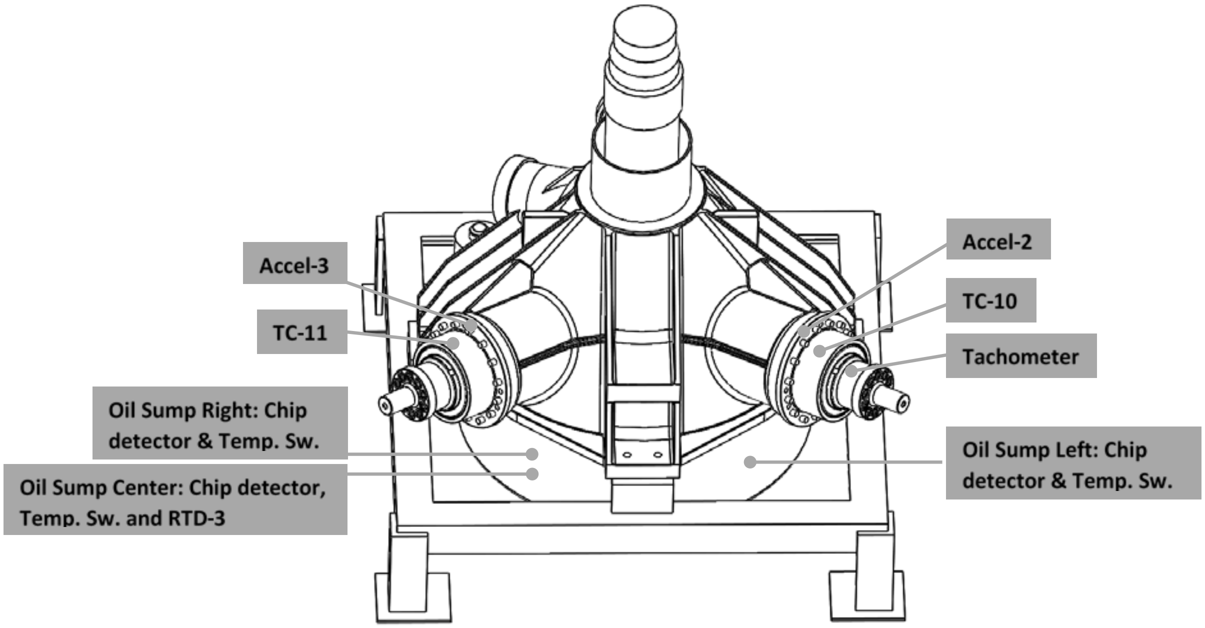

Fig. 7 Main module instrumentation, forward side

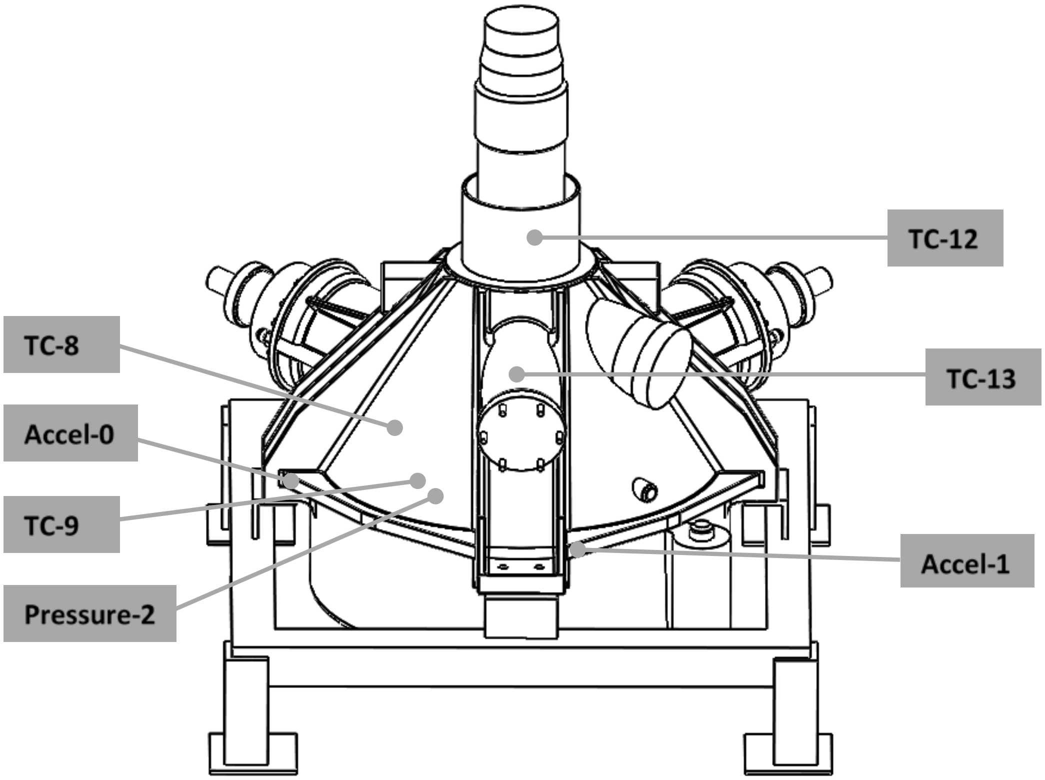

Fig. 8 Main module instrumentation, aft side

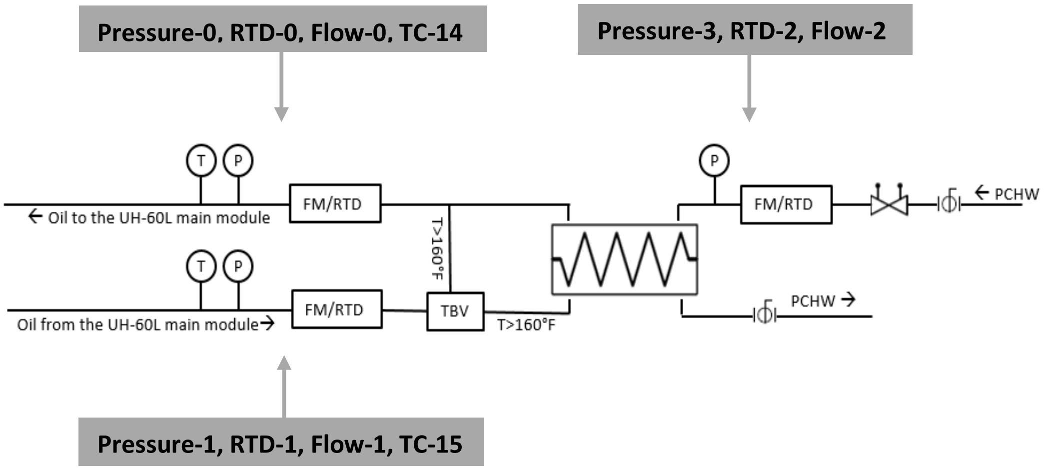

Fig. 9 **Oil-cooling cart instrumentation**

2.3 Summary of Verification Experiments

The primary goal of testing the transmission and its custom assemblies was to ensure proper operation for commissioning. Proper operation was defined by four major requirements:

1) The UH-60L main module generates oil pressure and flow through its internal scavenge pump.
2) The oil-cooling cart regulates oil temperature.
3) The PCHW flow control is robust to account for varying input-flow rates and transients.
4) Reference data are collected for a baseline understanding of anticipated oil pressures and flow rates for commissioning.

Given the requirements for a successful system checkout, three test protocols were identified to satisfy all four requirements with one test setup.

2.4 PCHW Flow-Control Verification

The first system test focused on the building's PCHW control system. The control system consisted of a flow meter, a proportional control valve, and two logic states. The flow meter was positioned downstream of the proportional control valve, opposite of the PCHW building-supply ball valve. The first logic state in the control system set the proportional control valve to 3.0 V if the flow meter read 2.0 gal/min or less. The 3.0 V setting opened the proportional control valve enough to allow flow through the system once the PCHW supply was opened and it allowed a flow rate of about 6 gal/min if the PCHW system was fully opened. The second logic state controlled the proportional control valve with a Proportional Integral Derivative (PID) control loop with a set point of 7.5 gal/min, if the flow meter read above 2.0 gal/min. The PID control loop provided a process control signal to the valve based on the flow-meter value, the 7.5-gal/min set point, and a maximum control signal of 4.5 V. This maximum value was established experimentally to keep the proportional valve partially closed at all times to prevent an inrush of PCHW from damaging the flow meter. With the building's PCHW ball valve fully opened, flow through the flow meter was limited to 21 gal/min with a 4.5-V setting. The 21-gal/min flow rate was well within the flow meter's calibrated range of 0 to 30 gal/min. The control-system operation was tested by manually actuating the PCHW supply ball valve while the main module was not spinning.

2.5 Main Module Spin Test

The second system test focused on the oil flow and pressure generated within the UH-60L main module at varying input adapter speeds. Slightly undersized for the application, the 20 hp motor was able to operate the UH-60L main module at full speed only after the oil was heated through frictional losses at relatively low speeds. Once the oil temperature reached 150 °F, the motor was able to reach the full operating speed with short-duration exceedances of the motor's full-load amps rating. During these experiments, the PCHW supply valve was closed to minimize residual cooling. Table 1 shows the schedule of controlled input motor speed, the geared input adapter speed, and the dwell time at each speed step. The second input adapter, main mast shaft, and tail take off pinion were allowed to rotate freely during the tests. The dwell times for speed steps above a commanded motor speed of 1,750 rpm were limited to 30 s to avoid overheating the motor. The speed-step sequence took the transmission through its operating range and provided baseline data for the modified test article. The regimented schedule would not be required given a motor with a higher power rating.

Table 1 UH-60L main module's speed-step sequence

Commanded motor speed (rpm)	Input adapter speed (rpm)	Dwell time (s)
1050	2851	60
1150	3150	60
1250	3451	60
1350	4053	60
1450	4356	60
1550	4655	60
1650	4952	60
1750	5249	30
1800	5394	30
1850	5543	30
1900	5689	30
1928	5769	30
1950	5835	30

2.6 Oil-Cooling Cart's Heat Exchanger and Thermal Bypass Valve Test

The third and final system test focused on the heat exchanger's ability to cool hot oil and the thermal bypass valve's operation across its temperature threshold. The transmission input speed was reduced to 3,451 rpm to avoid high motor-current faults, with the scavenge pump operating at a proportionally lower speed corresponding to this lowered input adapter speed. The chilled water supply was opened to allow flow through the heat exchanger after an oil temperature above the thermal bypass valve threshold (160 °F) was attained through frictional heating. Actuation of the proportional valve supplying chilled water to the heat exchanger and the action of the oil thermal bypass valve were observed in conjunction with oil temperature.

3. Results

3.1 PCHW Flow-Control Test Results

The PCHW flow-control test results show the PCHW was successfully controlled while simultaneously providing inrush-flow protection for the PCHW flow meter's calibrated range of 0 to 30 gal/min.

Figure 10 shows the PCHW flow-meter measurements through a sequence of supply-valve conditions, labeled 1 through 5 in the following list. The supply-valve position was controlled by hand and the proportional control-valve signal was not recorded for inclusion in the figure. Instead, the supply-valve position and proportional control-valve voltage were described as follows:

1) The supply valve was closed and the flow meter read 0 gal/min. As programmed in the first logic state of the PCHW control system, the PID control was off and the proportional control valve position process signal was set to 3.0 V because there was no flow through the system.
2) The PCHW supply valve was changed to fully open. The inrush flow was limited to about 6 gal/min because of the 3.0-V valve setting. The PID loop began controlling the proportional valve because the PCHW flow crossed the 2 gal/min programmed logic-state threshold. After some time, the flow value was controlled through the PID process signal to settle around the PID set point of 7.5 gal/min.
3) The PCHW supply was manually restricted to 6 gal/min, despite the PID control loop's attempt to increase flow. The PID loop saturated at its highest control value limit of 4.5 V.
4) The PCHW supply valve was changed to fully open. An inrush of PCHW flowed through the proportional control valve with a setting of 4.5 V due to the saturated PID control. The flow rate reached a peak of 21 gal/min before the PID control was able to start decreasing the flow rate. The PID control continued to decrease the flow rate until it settled around the set point of 7.5 gal/min.
5) The ball valve was adjusted transiently to observe the PID control's ability to maintain 7.5 gal/min. The PCHW supply was fully opened and the flow rate settled around the 7.5 gal/min set point.

This test showed the PCHW flow control is robust to account for varying input flow rates and protects the flow meter from an inrush above its calibrated range.

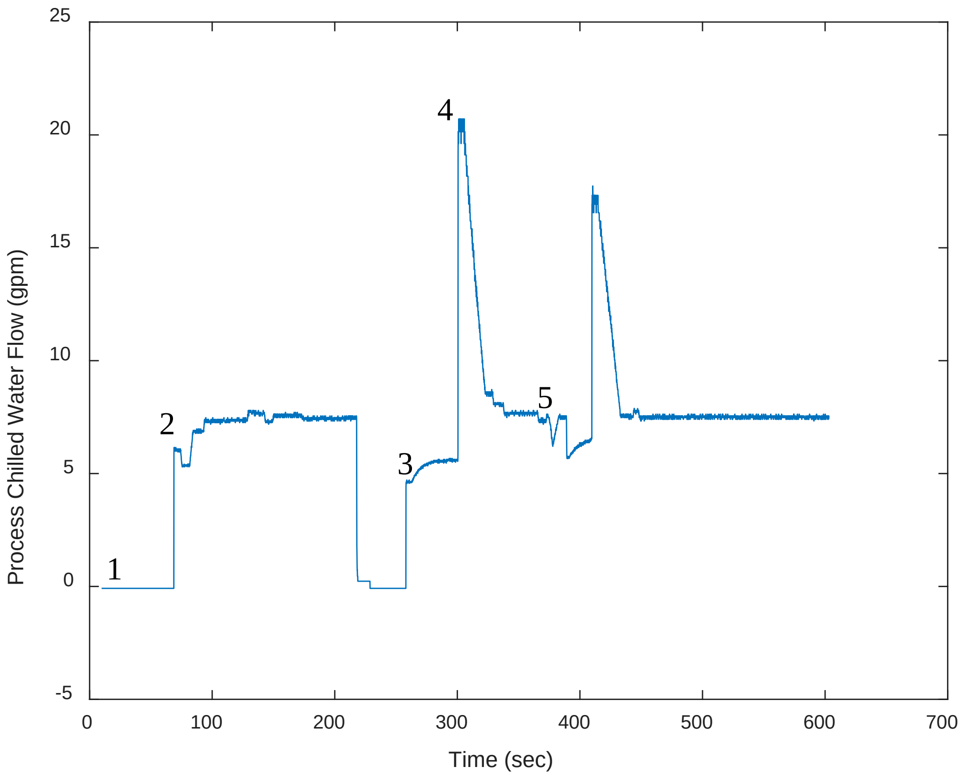

Fig. 10 PCHW flow-control sequence results

3.2 Main Module's Spin-Test Results

The UH-60L main module operation test results show oil pressure and flow were generated though the UH-60L main module as the input adapter was rotated. Figures 11 and 12 show the oil pressure and flow increased with increasing input adapter speed. At the nominal operating speed of 5,750 rpm, the UH-60L main module generated 39 psi at 23.5 gal/min, which corresponds to a 0.5-hp pump. The oil pressure and flow data from the main module spin test are representative of the main module under various torque loads since the pump power primarily depends on the transmission speed. The raw pressure and flow data were averaged at each steady-state speed step within the test sequence to correlate the oil behavior to the input speed. The results are plotted in Figs. 11 and 12 with standard-deviation error bars to show the relative difference between tests. The magnitude of the error was dominated by variation due to temperature drift, as the transmission continued to heat up throughout the test. Figures 11 and 12 serve as a good baseline for comparison during testing for proper UH-60L main module oil pump operation. Time-domain data plots of the flow meters, pressure transducers, RTDs, thermocouples, and accelerometers throughout the experiments are located in Appendix B for reference. During the course of these experiments, a chip-light indication was given by the transmission. On subsequent inspection, metallic chips were found on the main chip detector. These were removed for a precautionary composition analysis as described in Appendix C. The results did not uniquely identify the chip alloy and the transmission will be observed for further debris in future experiments.

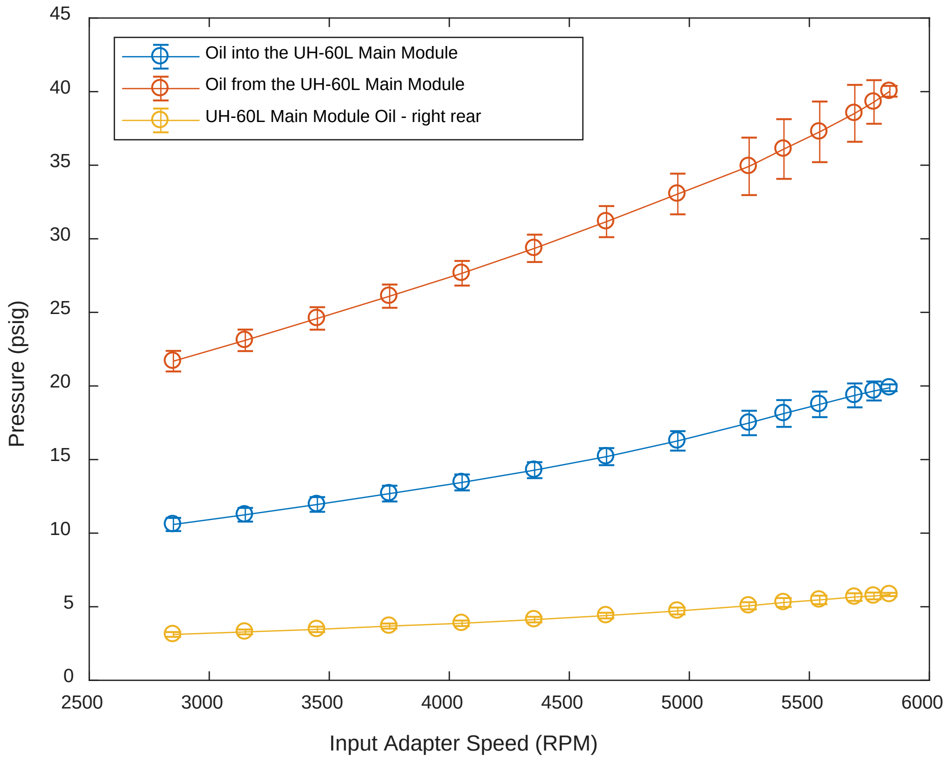

Fig. 11 UH-60L main module's average oil pressure over the input adapter's speed range

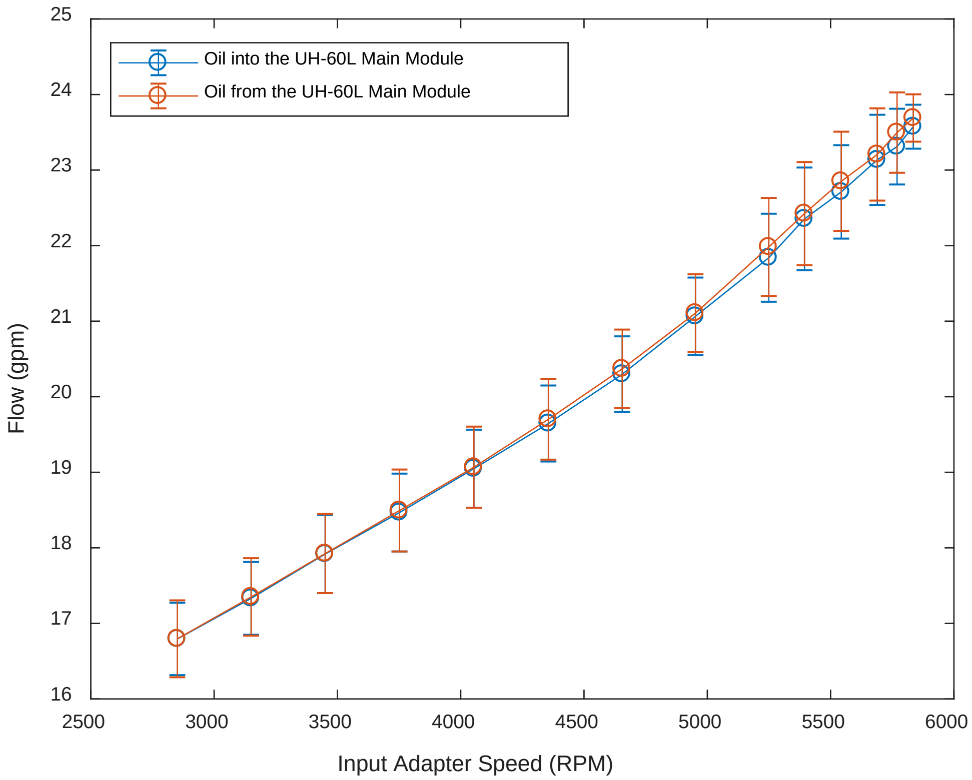

Fig. 12 UH-60L main module's average oil-flow rate over the input adapter's speed range

3.3 Oil-Cooling Cart's Heat Exchanger and Thermal Bypass Valve Test Results

The oil-cooling cart's heat exchanger and thermal-bypass valve test results verified operation of the heat exchanger and thermal bypass valve as designed. The oil temperature supplied to the transmission, shown in Fig. 13, started at 170.1 °F and was cooled to 140.8 °F as the PCHW flowed through the heat exchanger. The PCHW continued to flow through the heat exchanger, but the oil temperature stopped decreasing and rose to 142.6 °F. This increase in temperature occurred once the thermal bypass valve opened, bypassing the heat exchanger. The oil temperature began to drop after the peak because of transients in the system. The thermal transients could not be exercised with the 20 hp motor setup because of the motor current limit experienced while operating with cooler, more viscous oil. This test confirmed that the heat exchanger effectively reduced the oil temperature and that the thermal bypass valve changed position across its threshold temperature.

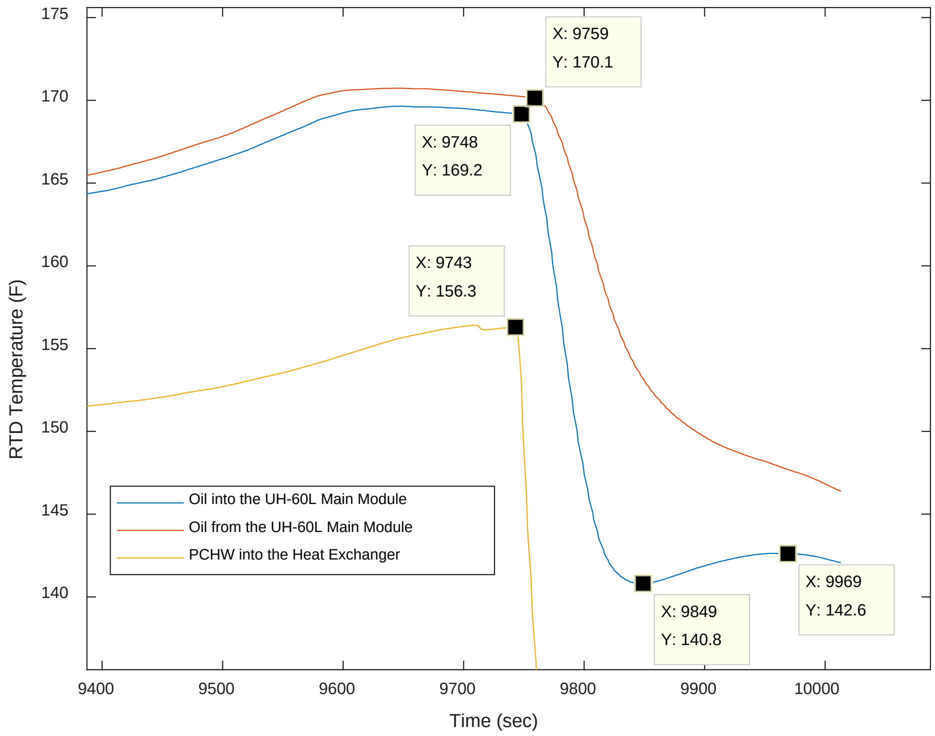

Fig. 13 UH-60L main module oil and PCHW RTD measurements during the thermal bypass valve's checkout test

4. Conclusions

This report described the choice of the UH-60 L/M improved durability gearbox's main module as a commissioning and first research test article. Modifications to the transmission inputs were made based on test-stand capabilities, and the design and operation of an auxiliary oil-conditioning system were described to allow this aircraft hardware to operate robustly in a laboratory environment. A series of three verification experiments demonstrated that the PCHW supply control was effective, the UH-60L main module generated oil pressure and flow, and the oil-cooling cart effectively cooled the oil with a thermal bypass valve operating around 160°F. Measured data for the oil pressure and flow were presented with a varying input speed, reflecting operation other than that experienced on wing. This verification of the transmission and auxiliary oil-conditioning system operation provides confidence in the subsequent commissioning of the VIPER testbed across a spectrum of loads.

5. References

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Appendix A. Vehicle Innovative Powertrain Experimental Research (VIPER) Test-Stand Operational Envelope

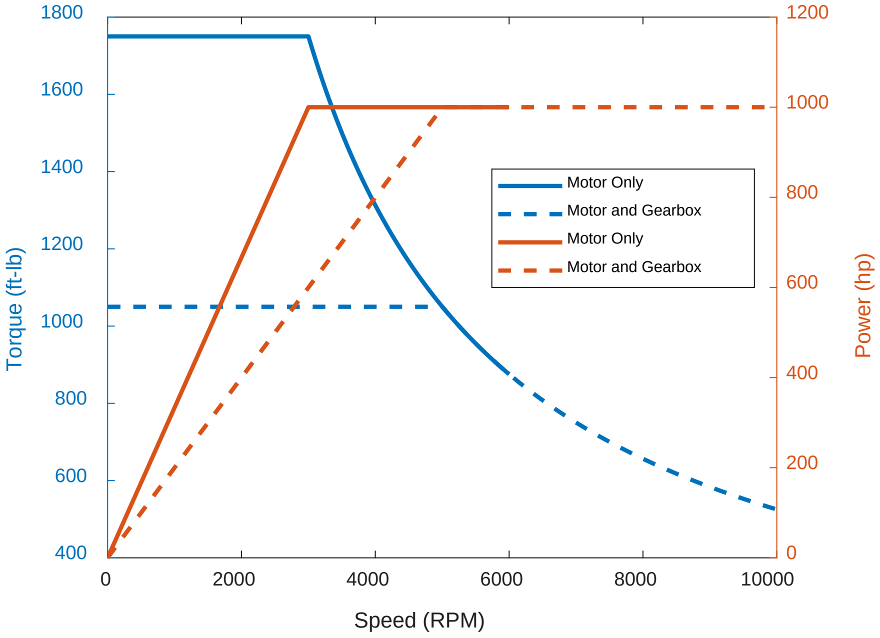

Fig. A-1 Torque and continuosly rated power envelopes for each 1000-hp rated transmission input, VIPER stand

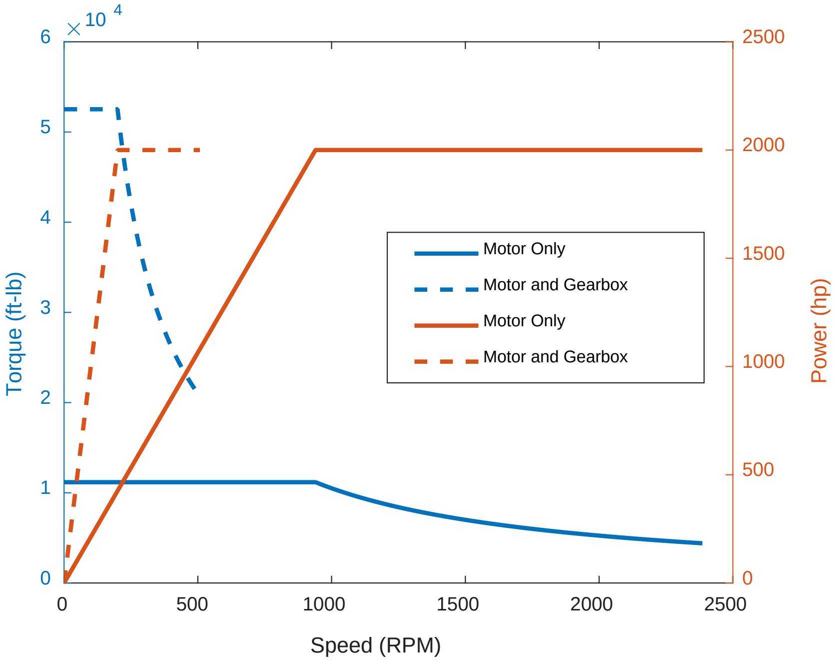

Fig. A-2 Torque and continuously rated power envelope for the 2000-hp rated transmission mast output, VIPER stand

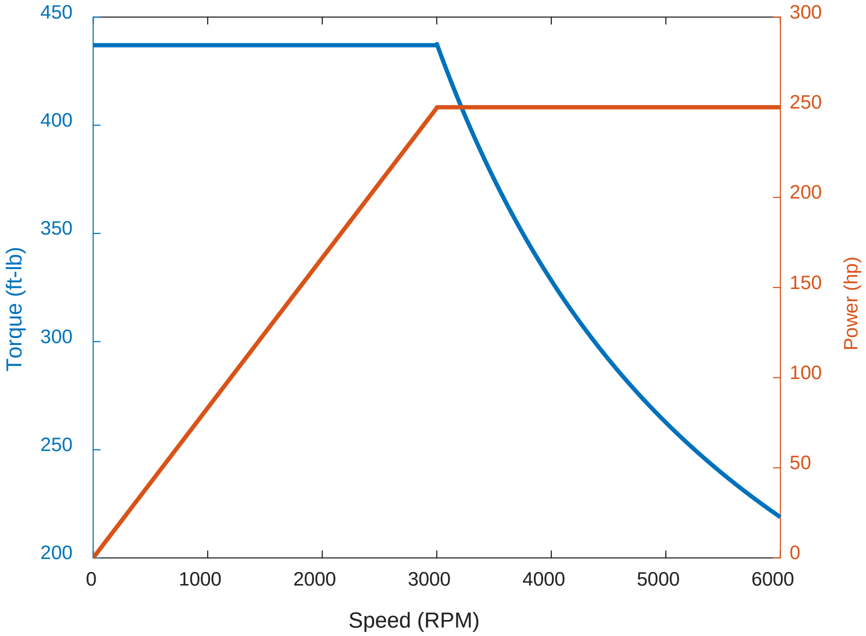

Fig. A-3 Torque and continuosly rated power envelope for the 250-hp rated transmission tail rotor output, VIPER stand

Appendix B. Time-Domain Experimental Data

This appendix provides time-domain data sampled during the checkout experiments for the commissioning test article, separated by signal type. The data were recorded during the main module spin test with three iterations of the speed-step sequence.

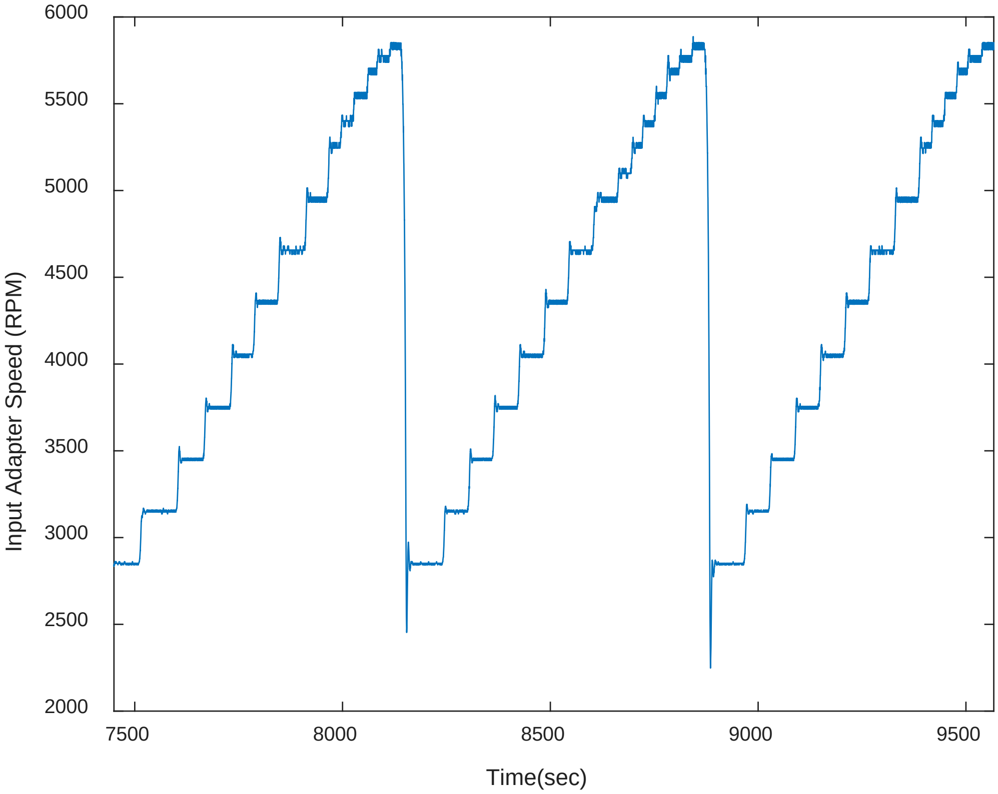

Fig. B-1 Main module operation test's raw data: input adapter speed

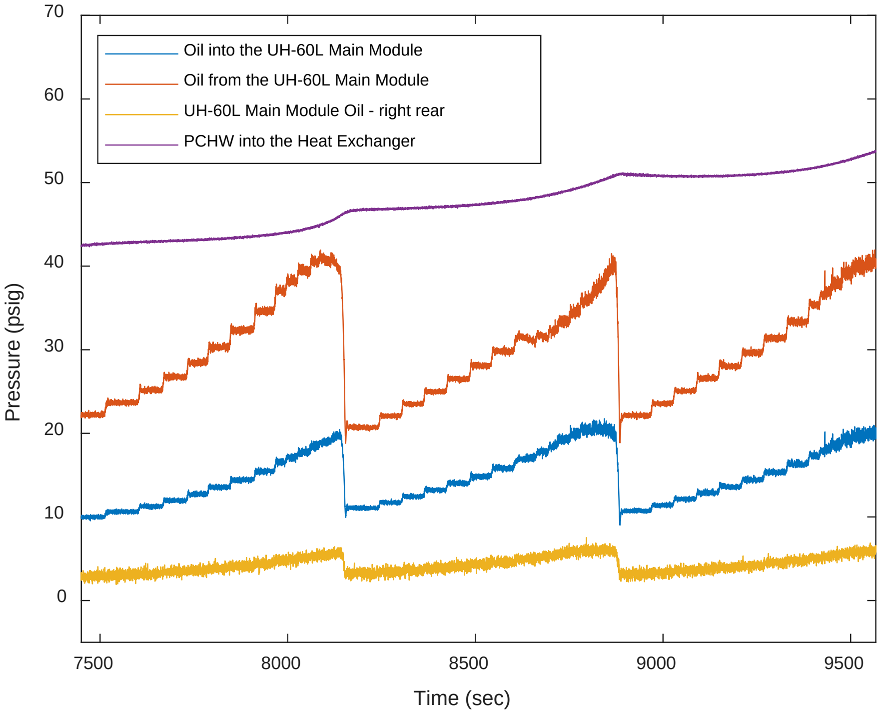

Fig. B-2 Main module operation test's raw data: pressure measurements

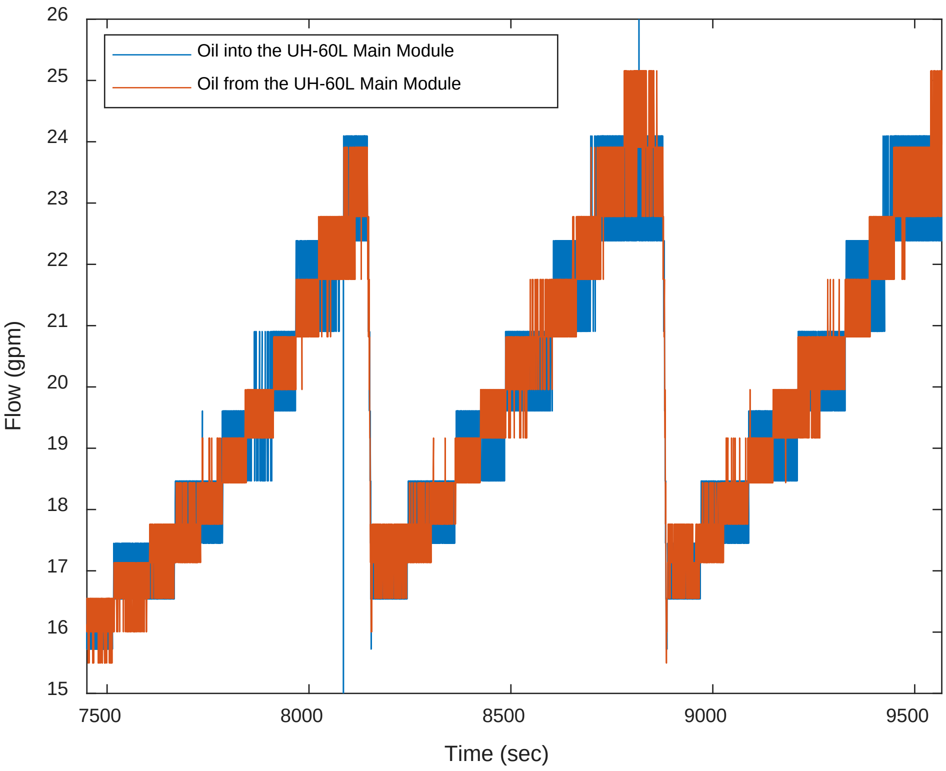

Fig. B-3 Main module operation test's raw data: flow measurements

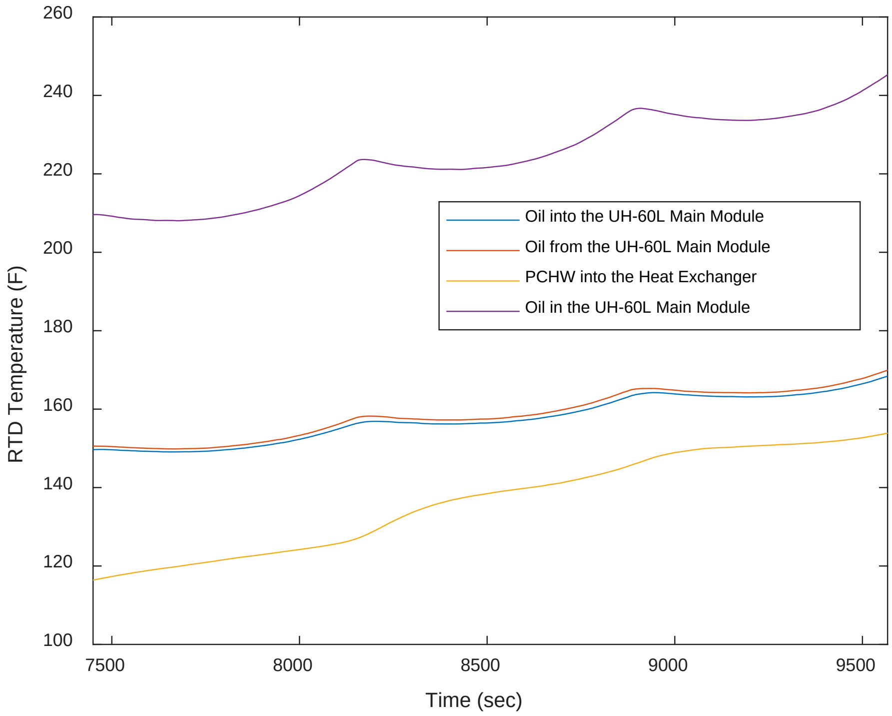

Fig. B-4 Main module operation test's raw data: resistance temperature device measurements

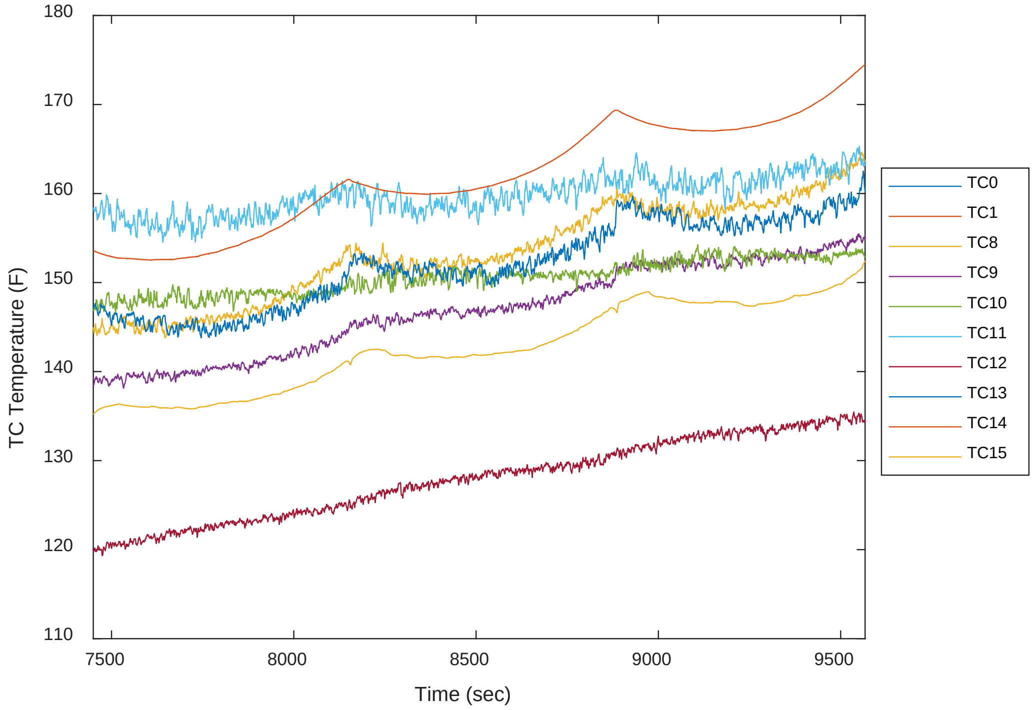

Fig. B-5 Main module operation test's raw data: thermocouple measurements

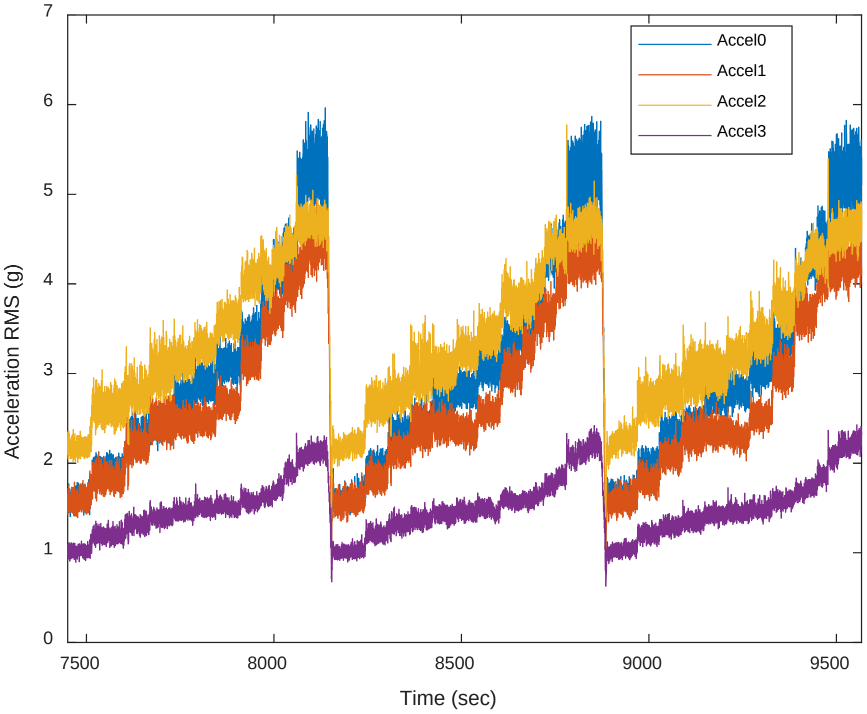

Fig. B-6 Main module operation test's raw data: accelerometer measurements

Appendix C. Transmission Wear Debris

Chips were collected from the UH-60L main module chip detector after testing. Testing continued despite the chip detector light because of previous false-positive detections. The chips were all less than 1 mm long with the exception of one 5.2-mm chip spanning the chip detector gap. An assortment of chips were analyzed with a scanning electron microscope (SEM) for their elemental composition. With one exception, all chips contained chromium and nickel alloying elements consistent with 4340 or 9310 gear-steel compositions. However, the exact alloys of the chips were not uniquely distinguishable by the methods immediately available. The history of the decommissioned transmission is unknown and further debris generation will be monitored. The morphologies of the chips examined with the SEM are shown in Fig. C-1.

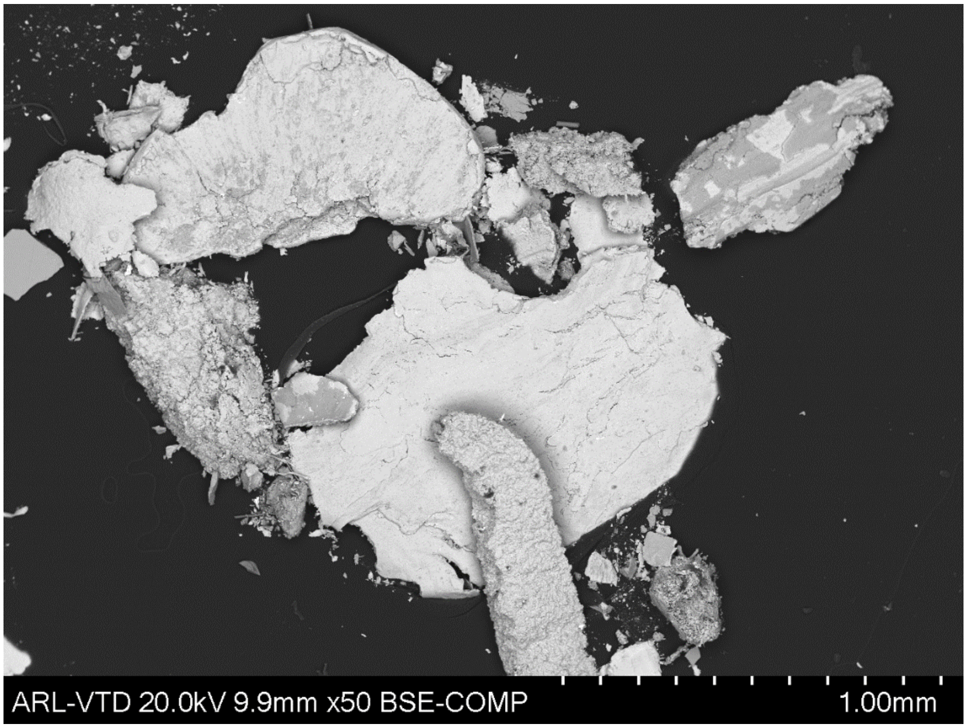

Fig. C-1 Main module chips collected from the chip detector

List of Symbols, Abbreviations, and Acronyms

AC	alternating current
ARL	US Army Research Laboratory
PCHW	process chilled water
PID	Proportional Integral Derivative
rpm	revolutions per minute
RTD	resistance temperature device
SEM	scanning electron microscope
VTOL	vertical takeoff and landing

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