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Laying the Foundation for Project Interception: Experiments, Modeling, and Overhauls for Rotorcraft Transmissions for AI/ML Prognostics

by Mark Riggs, Adrian Hood, Ryan Emerson, and Marc Gonzalez

NOTICES

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14. ABSTRACT
Project Interception is an unfunded research effort to improve the readiness and operational availability of U.S. Army VTOL drive systems by advancing fault detection capabilities for main gearbox transmissions. Significant groundwork was laid in FY24 and FY25 before funding lines were reallocated. The goal of this report is to preserve the foundation for future use. The report describes an introduction to Project Interception, its early progress, and an outline for future work.

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1. Introduction[*]

Project Interception (PI)'s goal is to improve the readiness and operational availability of U.S. Army vertical takeoff and landing drive systems by advancing fault detection capabilities for main gearbox (MGB) transmissions (Wade et al. 2017). The origin of the project began from a simple thought exercise:

> Damaged transmissions are required to collect accelerometer data for damage detection algorithms, but seeded fault experiments are expensive and not always representative of the real world. Could we "intercept" damaged transmissions from the field for experiments before overhaul?

The thought exercise materialized into the proposed workflow concept outlined in Figure 1. The current workflow (shown in Figure 1a) starts when damaged transmissions are removed from service and sent to a Defense Logistics Agency (DLA) warehouse where they are logged with a reason code such as "804 SCHEDULED MAINT.," "170 CORRODED," or "923 INSPECTION REQUIRED," among others. Annually, the Aviation and Missile Command (AMCOM) develop an Army sustainment maintenance plan based on global aviation requirements, and this plan is executed by the Powertrain and Production floor at Corpus Christi Army Depot (CCAD). Overhauled MGBs are then sent back to DLA and are ultimately returned to service. The U.S. Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL)'s workflow proposal (shown in Figure 1b) is to intercept a subset of transmissions (with damage reason codes) between DLA and CCAD for experimentation before overhaul.

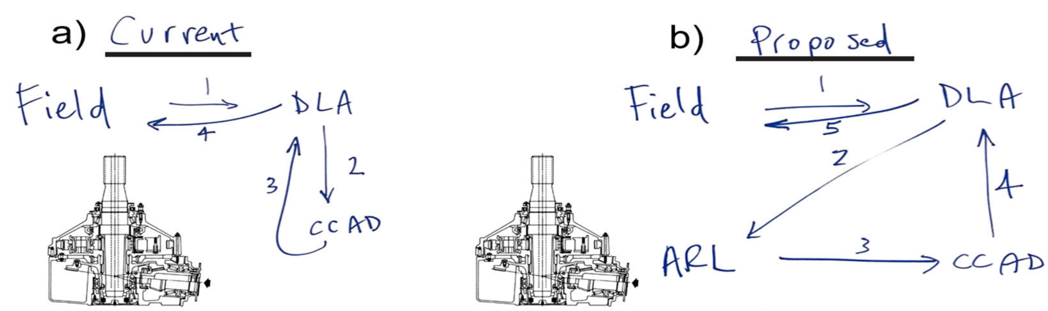

Figure 1. a) The current workflow for damaged transmissions. b) The proposed PI workflow.

[*] ChatGPT Government 3.1 was used to help refine the clarity and structure of writing certain sections and sift through extensive e-mail chains to generate a summary of the conversations among the players in the Interagency Asset Acquisition Guide. All substantive content was written by the authors. The authors carefully reviewed, fact-checked, and edited all material generated by ChatGPT to ensure accuracy and alignment with the report's objectives.

Collecting and pairing diagnostic data (e.g., from accelerometers and acoustic emission sensors) with a point-specific failure (e.g., a 2-mm^2 spall that is 50 μm deep near the tip of a tooth on the input pinion) is outside the scope of the Depot Maintenance Work Requirement for overhauling MGBs. Therefore, this workflow gives ARL an extremely valuable opportunity to collect sensor data on a damaged MGB before the damage mechanism is recorded during overhaul.

AI/ML tools are ideally situated for performing this analysis of diagnostic data labeled against specific overhaul findings. However, training AI/ML models will require substantially more damaged transmission data than can be provided through intercepted transmissions alone. The approach proposed in PI is to use the intercepted transmission data to validate an analytical transmission model that will produce a large training data set.

2. Interagency Asset Acquisition Guide

This section outlines the procedural and relational lessons learned from PI to acquire damaged transmissions for research experiments. The project was ultimately suspended due to budget constraints, but the challenges faced and solutions found in navigating the Army's logistics and sustainment enterprise provide a critical blueprint for any future resumption of this work or similar research efforts. This section serves as a "how-to" guide for future ARL scientists to minimize the significant friction and delays experienced.

The primary obstacle was not technical; it was a combination of procedural gaps and a fundamental communication barrier. ARL does not "speak logistics," and the operational personnel at CCAD, DLA, and the AMCOM do not "speak research." This created a gap between ARL's research-oriented mission and the process-driven, operational mission of the materiel organizations. These logistics bodies had no prior business processes in place with ARL and operate within a culture of strict adherence to established, audited procedures, making any request outside that criterion difficult to process.

2.1 Building the Partnerships: A Two-Front Approach

Experience shows that any future effort requires securing two distinct agreements in parallel. One is not sufficient without the other, and they should be pursued simultaneously from the project's outset. The two fronts are a technical partner and a logistics partner.

The technical partners for PI reside at CCAD. The initial objective is to secure buy-in from the on-the-ground leadership responsible for the asset, which would be

AMCOM Logistics Center. In addition, support from the Systems Readiness Directorate located at CCAD is important to gain engineering wisdom and technical oversight during the teardown analysis. An initial high-level introduction among Senior Executive Service leadership was important for showing high-level support and connecting the right directorates. This introduction was followed by a critical face-to-face visit. The meeting allowed ARL engineers to explain the scientific goals directly to the shop floor leadership (Director of Powertrain Production). This built a strong, informal "gentleman's agreement." The Director understood the project's value and agreed to have his team perform the minor extra work (taking photos and measurements) at zero cost to his operation. (There is a warning that the technical partner relationship is susceptible to personnel turnover. The initial champion was replaced by a new director who was less comfortable operating outside of formally documented procedures and required a written memorandum of understanding and funding, effectively resetting progress. Patience, clear communication, and openness to a new way of operating helps establish a new agreement and keep the project moving forward.)

The logistics partners for PI were the Materiel Support Directorate at AMCOM and the supply planners at PM Utility (Project Manager, Utility Helicopters). The agreement with the logistics partners will need to be more formal than with the technical partner because of the movement and tracking of an Army asset. This proved to be the most significant hurdle. The ARL team never directly engaged the ultimate decision-maker. Behind the scenes, the problem was escalated to the Supply Planning Division Chief at PM Utility. This Chief, in turn, identified a key agent to handle the request. The key agent's success was a major breakthrough. The agent's success was not due to "heavy lifting" but to her creative, "get-to-yes" posture. Instead of defaulting to "no" for a nonstandard request, she took the initiative to pick up the phone, find the right people, and translate ARL's needs into a language the logistics system could understand. She was the crucial link who identified the procedural solution. In this case, the solution was an "AGREEMENT FOR THE LOAN OF U.S. ARMY MATERIEL," Department of the Army Form 4881, shown in the Appendix.

2.2 A Blueprint for Future Success

To resurrect this project, future ARL scientists should give equal effort from the beginning to the technical work and the bureaucracy. The gentleman's agreement that felt like a quick victory was ultimately insufficient. The path forward requires a deliberate strategy to find creative problem solvers within the formal structure.

1) Request a Creative Problem Solver: The first and most critical nontechnical task is to contact the Supply Planning Division Chief at PM Utility. Do not ask the chief to solve the problem directly. The strategic "ask" is for them to identify an individual on their team with a creative, get-to-yes mindset who can navigate a nonstandard request. This approach respects the chain of command while specifically asking for the type of person needed for success.
2) Collaborate with the Identified Problem Solver: Once this individual is identified, work with them collaboratively. Their value is their institutional knowledge and their willingness to find a solution. Clearly provide them with the project's requirements and trust them to guide you to the appropriate procedural path.
3) Secure Technical Leadership Buy-in: In parallel with the AMCOM engagement, conduct a face-to-face visit with the leadership at the depot (e.g., CCAD). The goal is to find a leader with a "big picture" mentality who understands the value of the research and is willing to support the effort once the official pathway is cleared by AMCOM.

By following the blueprint of prioritizing a direct request to leadership to identify a creative problem solver while simultaneously building the on-the-ground technical relationship, any future project can significantly increase its chances of navigating the bureaucracy to successfully acquire damaged transmission test assets.

3. Intercepted Transmission Experiments

PI made early progress with minimal resources. The current laboratory capabilities and existing technical expertise enabled two baseline transmissions and three intercepted transmissions to be evaluated quickly. The experimental setup, representative data, and an overhauled transmission failure analysis are presented to give a starting point for future research.

3.1 Experimental Setup and Test Matrix

The intercepted transmissions were operated within the Vehicle Innovative Powertrain Experimental Research (VIPER) testbed to characterize the housing's vibration signatures. VIPER (shown in Figure 2) has four drivelines: two 1000-hp inputs, one 2000-hp mast output, and one 250-hp tail output (Riggs and Hood 2021). Although VIPER does not reach the UH-60/Blackhawk's full power, it does reach full operating speed of the main module. Full operating speed allows for a proper analysis of shaft harmonics, gear mesh frequencies, and ball pass frequencies.

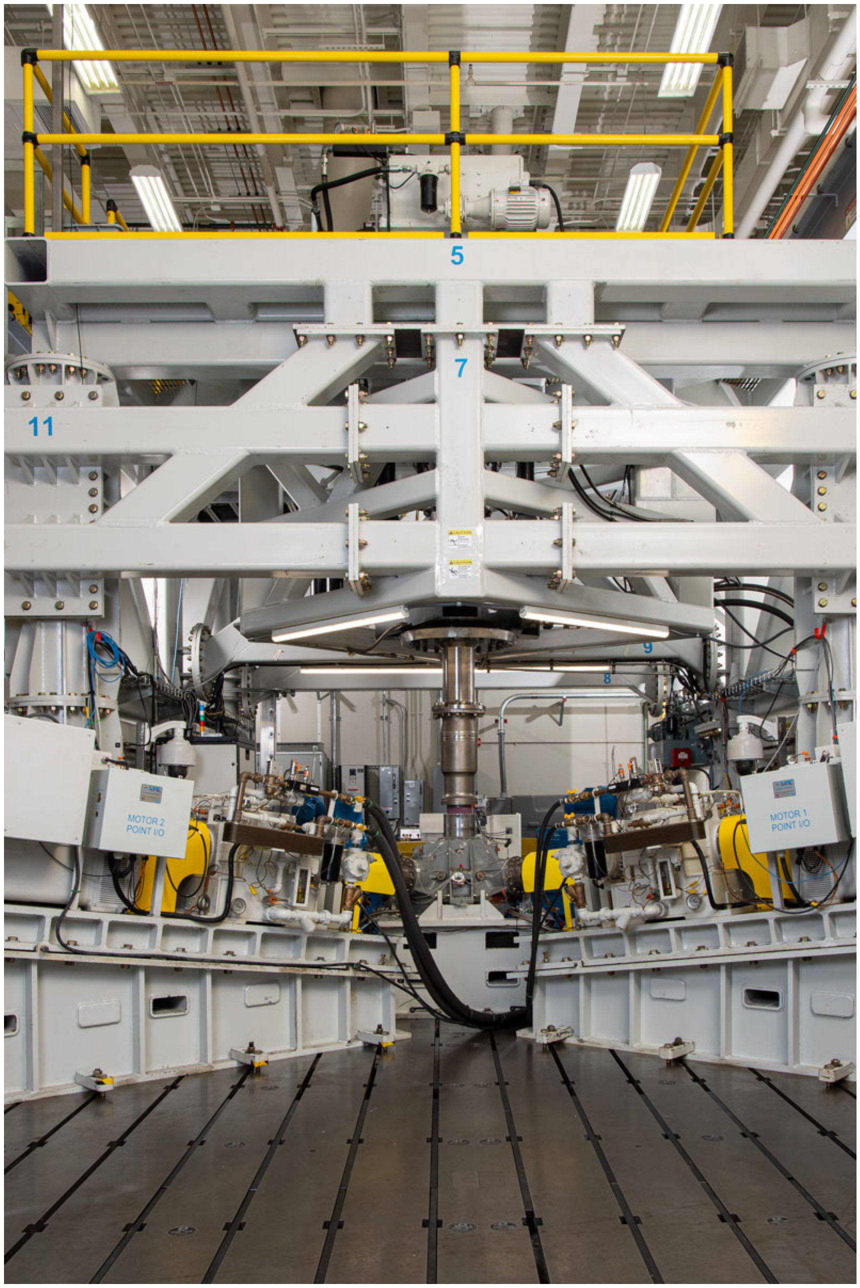

Figure 2. VIPER overview.

Transmission accelerometers were placed near the inputs, tail rotor, mast, and around the ring gear. Ring gear placements were equally spaced at 20° to ensure sensitivity to faults withing the planetary system. Accessible bearings at the inputs and outputs of the transmission were monitored with radial and axial accelerometers. Thermocouples were strategically placed to understand the transmission's housing temperatures. Example schematics of the instrumentation placements are shown in Figures 3 and 4.

44 Accelerometers and 4 AE sensors:

Accel Number	Channel Name		
1	TA Ring #1	23	Input 2 top 1
2	TA Ring #2	24	Input 2 top 2
3	TA Ring #3	25	Input 2 side 1
4	TA Ring #4	26	Input 2 side 2
5	TA Ring #5	27	Mast radial 1
6	TA Ring #6	28	Mast radial 2
7	TA Ring #7	29	Mast axial 1
8	TA Ring #8	30	Mast axial 2
9	TA Ring #9	31	Tail Inner Top 1
10	TA Ring #10	32	Tail Inner Top 2
11	TA Ring #11	33	Tail Inner Side 1
12	TA Ring #12	34	Tail Inner Side 2
13	TA Ring #13	35	Tail Outer top 1
14	TA Ring #14	36	Tail Outer top 2
15	TA Ring #15	37	Tail Outer side 1
16	TA Ring #16	38	Tail Outer side 2
17	TA Ring #17	39	OEM Left Side loc8
18	TA Ring #18	40	OEM Right Side loc13
19	Input 1 top 1	41	Input 1 Jack Shaft radial
20	Input 1 top 2	42	Input 1 Jack Shaft axial
21	Input 1 side 1	43	Input 2 Jack Shaft radial
22	Input 1 side 2	44	Input 2 Jack Shaft axial

AE sensors are located at: Input 1, Input 2, Mast, and Tail

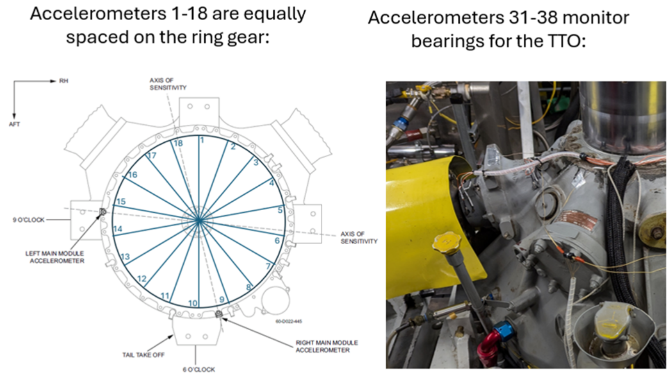

Figure 3. Accelerometer placement information.

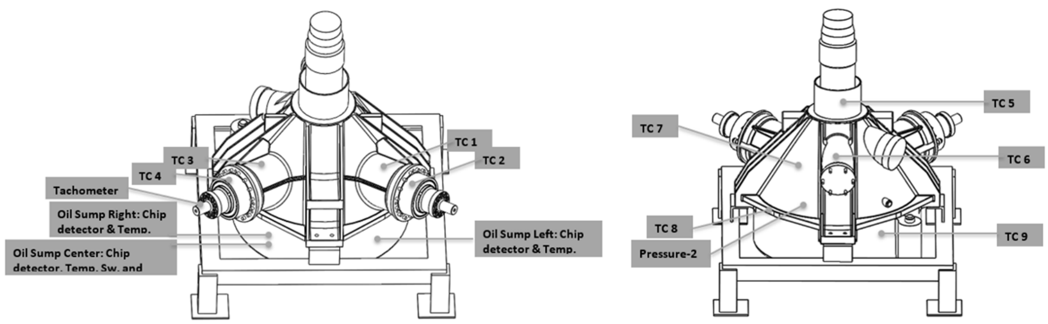

Figure 4. Additional transmission sensor locations.

Wear debris was monitored as part of the auxiliary lubrication cart. The transmission filter was relocated with custom hardware to allow for an in-line Gastops oil debris monitor. Figure 5a shows the traditional oil outlet of the filter is closed. Figures 5b and 5c illustrate that the oil filter housing is replaced with an adapter to flow unfiltered oil into the debris monitor. Figure 5d shows the transmission oil passes through the Gastops sensor and a custom filter housing (red) before the oil flows into the cart for temperature control. The Gastops sensor detects particle counts and bins the particles based on size. The oil cart also monitored operating temperature, flow rate, and pressure (see the schematic in Figure 6).

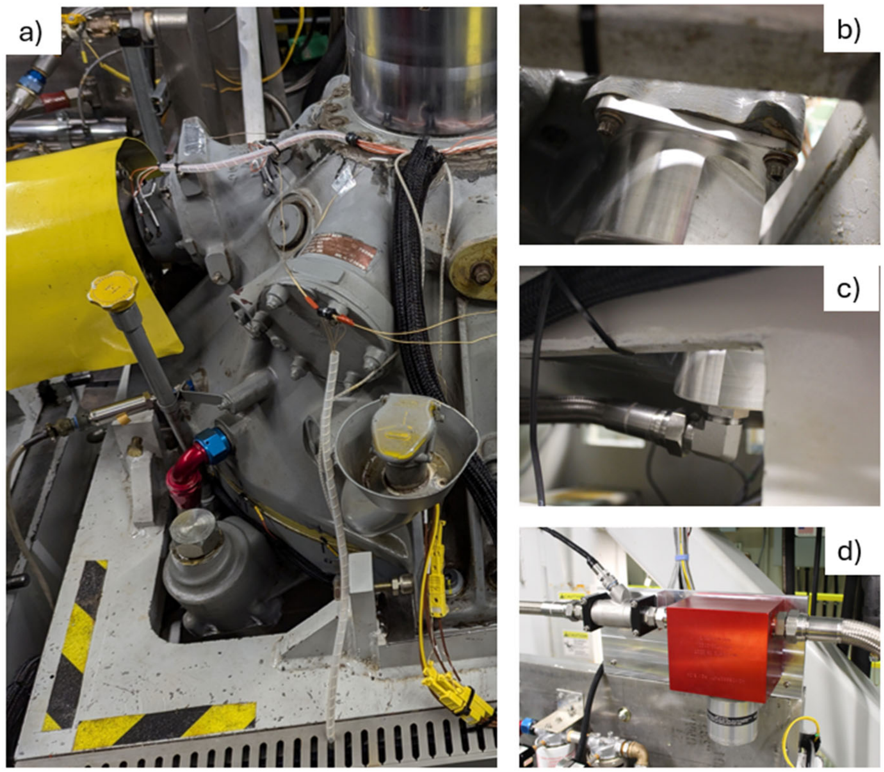

Figure 5. (a–d) Gastops oil debris monitor adapters and mounting location.

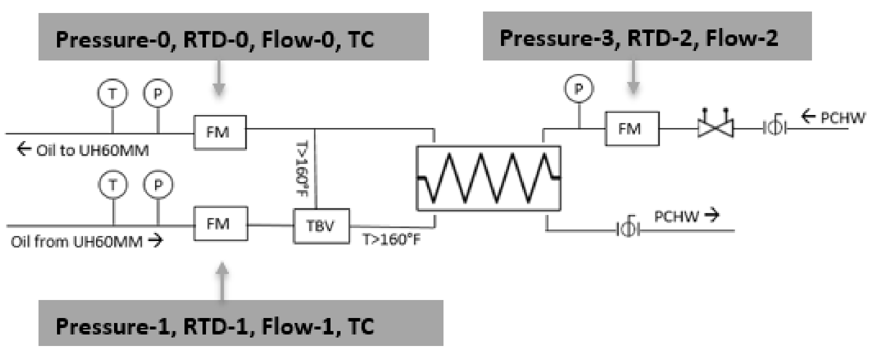

Figure 6. Oil cart sensors.

The test matrix intent was to capture the dynamics of damaged components without damaging the transmission further. Increasing the amount of damage within the transmissions is undesirable because the Army assets are scheduled for an overhaul and reinsertion into the field. However, data repeatability needed to be established, and multiple, steady-state operating conditions were desired. The test matrix shown in Table 1 was run three times per day for 3 days before the overhaul.

Table 1. Test matrix.

Step	Motor 1 and Motor 2			Motor 3			Motor 4		
	Torque (ft-lb)	Speed (rpm)	Power (hp)	Torque (ft-lb)	Speed (rpm)	Power (hp)	Torque (ft-lb)	Speed (rpm)	Power (hp)
Warm-up	**88**	3000	50	3122	**134.6**	80	**50**	2148	20
1	**731**	5750	800	31,553	**258**	1550	**63.8**	4116	50
2	**913**	5750	1000	39,695	**258**	1950	**63.8**	4116	50
3	**913**	5750	1000	35,624	**258**	1750	**319**	4116	250
4	**913**	5750	1000	38,169	**258**	1875	**159.5**	4116	125
5	**913**	5750	1000	39,695	**258**	1950	**63.8**	4116	50
6	**822**	5750	900	35,624	**258**	1750	**63.8**	4116	50
Cooldown	**200**	3000	114	8116	**134.6**	208	**50**	2148	20

Notes: 1) All steps were run for 5 min; 2) a vertical force of 20,000 lb on the mast simulates lifting forces; and 3) bold parameters were controlled and non-bold values are ideal without losses.

3.2 Example Experimental Data Collected

Five transmissions were operated as part of the PI before funding was cut from the supporting mission line. These transmissions consisted of two baselines (one owned by ARL and one owned by Naval Air Systems Command; NAVAIR) and three intercepted transmissions (PI1, PI2, and PI3). PI1 was removed from service due to a carrier life timeout. This transmission was not the intended interception target, but it provides an interesting perspective as a timed-out transmission. PI2 and PI3 were removed from service after thousands of flight hours with an "internal failure" code accompanied by a note stating, "excessive metallic chips." There was concern that a damaged transmission may not perform the test matrix, but each transmission ran through the test matrix at least three times per day for 3 days without issue.

Accelerometer data from the transmission experiments are interpreted through box plots. Each box plot instance represents one accelerometer's vibration data for that day of testing. One representative day was chosen for each transmission, and the data was labeled with the transmission's name. Several condition indicators (CIs) were calculated for each transmission, including root mean square (RMS), Crest, energy ratio, FM0, FM4, kurtosis, M6A, M8A, NA4, and VAR. RMS acceleration in g's was chosen to be the representative CI for this report. Accelerometers 1–18 are presented in Figure 7 to show the ring gear data for all five transmissions. The PI1 transmission clearly stands out as having the highest RMS vibration levels. PI1 likely has the highest vibration levels for the planetary gear system because its carrier has timed out.

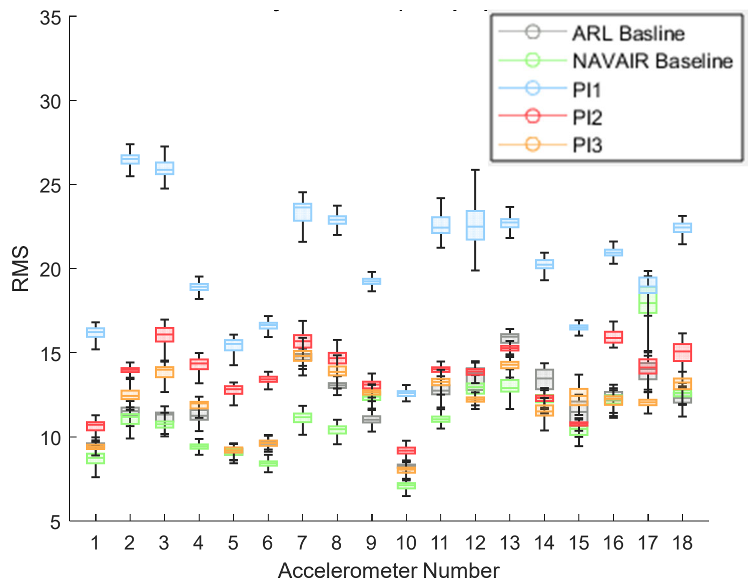

Figure 7. RMS values for all ring gear accelerometers (1–18) for all five transmissions.

An easier way to visualize the 18-ring gear accelerometers is with a polar plot. Polar plots are formed by plotting all three runs for 1 day with the median value placed at the corresponding location around the ring gear. For example, accelerometer 1's median magnitude value is plotted at the 0° location on the polar plot. Accelerometer 2's median magnitude value is plotted at the 20° location on the polar plot. Because the boxes are removed from the plots, 3 days of testing are plotted to show the results are consistent. For example, PI1 is plotted with three shades of blue. Each transmission has good repeatability shown by how closely the box plot median values for each color overlap, as shown in Figure 8.

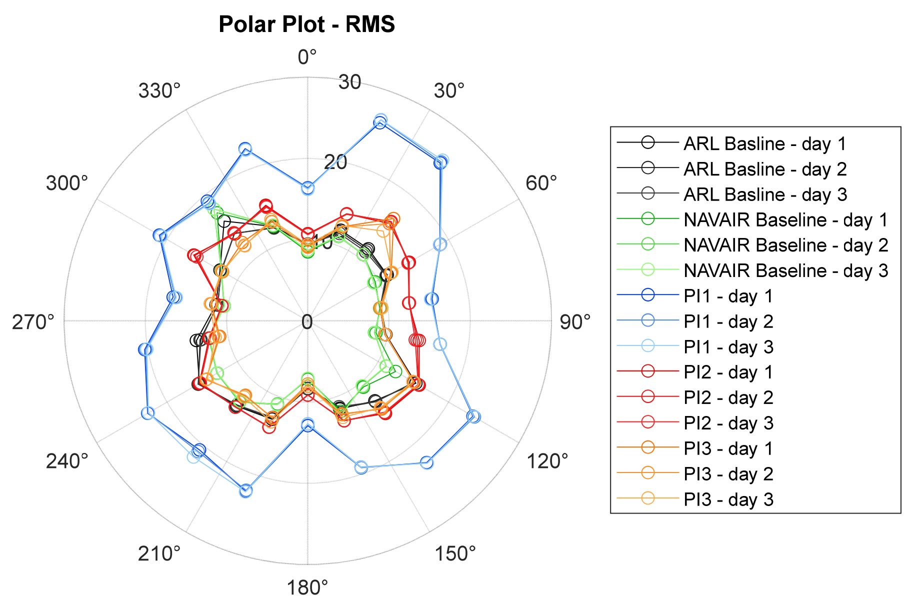

Figure 8. Polar plot of ring gear accelerometers.

An interesting trend develops when ring gear accelerometers are plotted onto a polar plot. All accelerometer values are reduced when the accelerometer aligns with a transmission mounting location, which are located at 0°, 90°, 180°, and 270°. This information could help inform optimal accelerometer placement with the largest response values, including legacy accelerometer placements.

The polar plot also demonstrates the limited use of some CIs. PI1 clearly stands out as having higher vibration levels, but PI2 and PI3 do not show any type of damage from RMS signals around the ring gear. This was also true for the other CIs we viewed for this data. Accelerometers more local to the damage may improve, but the number of accelerometers on a fielded transmission is limited. Limited accelerometer counts on fielded transmissions may benefit from an AI/ML analysis of the raw vibration data to extract patterns that traditional CIs do not detect.

3.4 Overhaul Analysis

The primary drawback of PI is that the location and severity of damage within the intercepted transmissions are unknown. There is also a risk that the fault in the transmission of interest is due to something other than a gear or bearing. This risk was mitigated through discussions between ARL subject matter experts and the technically experienced personnel on the Powertrain Production floor. Ultimately, the criteria were set to evaluate transmissions with more than 500 flight hours and a reason code indicating activity by the metallic chip detector. This approach is intended to provide MGBs with the highest likelihood of having a gear or bearing fault. The damaged component's location and severity are identified during overhaul analysis and relayed to the ARL researchers for application into the analytical model.

The three intercepted transmissions have been inspected during overhaul by CCAD. PI1 and PI2 did not have notable damage. PI3 showed significant damage from the overhaul, and wear chips were collected before the transmission was shipped out of ARL's facility. Figure 9 shows the wear chips on the transmission center chip detector and their placement on a puck for scanning electron microscope (SEM) elemental analysis. Nine chips were analyzed. All chips were bearing steel material except for chip 5, which was gear steel material.

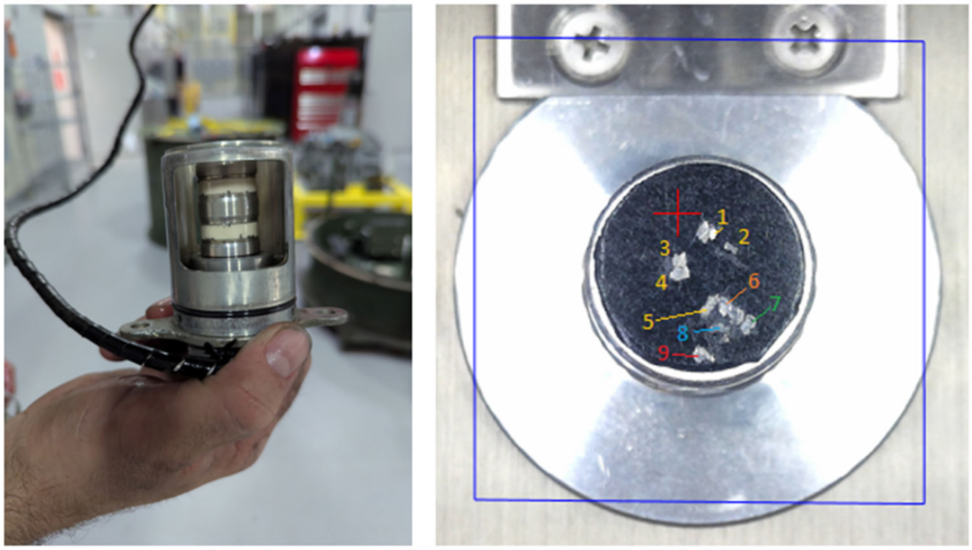

Figure 9. PI3 chips that were analyzed in the SEM.

The overhaul photographs agreed with the chip analysis with heavy damage to a tapered roller bearing (shown in Figure 10). These pictures and additional images taken during the overhaul would be used to characterize the bearing fault in a dynamic model if PI gains funding for continued work. The experimental data associated with PI3 would then be compared with the model data for validation.

Figure 10. PI3 bearing damage found during overhaul.

In addition to the chips that were collected before shipment, the Gastops oil debris monitor detected chips during operation that were not collected on a chip detector in the transmission. These chips passed through the transmission oil pump to the VIPER auxiliary lubrication cart and were counted before entering the filter housing. Detected chip sizes, estimated in thousands of an inch (thou), are categorized into bins to further quantify results and to distinguish between normal wear (low counts in bins 1 and 2) and signs of failure (counts in bins 3 and 4). Intercepted transmissions show significantly higher chip counts in Table 2 than the baseline transmissions. Further investigation into the timing of the chip detections within the elapsed time of the experiment data could be useful to correlate chip production with accelerometer and acoustic emission CI values.

Table 2. Gastops oil debris monitor chip counts for all five transmissions.

Transmission	Bin 1 (<249 thou)	Bin 2 (250–320 thou)	Bin 3 (321–490 thou)	Bin 4 (491–760 thou)
ARL baseline	13	4	1	0
NAVAIR baseline	10	3	0	0
PI1	30	10	0	1
PI2	40	13	2	0
PI3	31	25	9	0

4. Analytical Modeling: Finite Element/Contact Mechanics (FE/CM)

PI's analytical model builds on experience gained from past dynamic transmission models. Although damaged transmissions have not yet been simulated, a baseline UH-60/Blackhawk model is well underway, and the foundational elements are in place—including validated methodologies for gear generation and housing dynamics. These capabilities position full integration of the drivetrain and housing as a logical next step and will ultimately enable full-system simulations that unlock the model's potential for sensor optimization and diagnostic applications.

4.1 Modeling Capabilities: FE/CM

The Calyx Transmission3D software (Advanced Numerical Solutions, LLC) is used for modeling capabilities within PI. The elastic contact between meshing gears is calculated using a combined FE/CM method (Vijayakar 1991). This method accurately captures the contact pressure distributions and the resulting elastic deflections by breaking the displacement field into near- and far-field contributions.

- Near-field contributions: Displacements near the contact zone are calculated analytically. The primary assumption is that the resultant force from each contact cell elastically deforms material near the tooth surface. This deflection is calculated with a point load acting on an elastic half-space.
- Far-field contributions: Displacements far away from the contact zone are determined using a finite element formulation. The finite elements

accurately capture elastic deformations due to tooth bending, gear blank torsion, and deflections due to other elastic elements in the system.

The near- and far-field solutions are paired at a matching interface. The interface is defined at a distance sufficiently far from the tooth surface, resulting in a negligible displacement contribution from the analytical near-field solution.

The contact formulation is efficient and enables dynamic analysis. Displacements of all nodes on the gear body and tooth are numerically calculated at a specified rotation speed using Newmark time discretization. The FE/CM method captures elastic teeth contact at each instant of the mesh cycle (Parker et al. 2000a). The elastic teeth contact analysis is robust to account for extreme conditions, including large vibration amplitudes that cause a tooth contact loss (Parker et al. 2000b).

Special finite elements are used on the tooth surface to accurately capture the involute geometry and the elastic deformations that result from loaded gears. These finite elements use many nodes along the tooth profile to accurately represent the involute tooth surface. The shape functions used in these elements have continuous first derivatives to accurately capture local curvatures of the deformed tooth profile.

4.2 Baseline Modeling Initiation

A solid model of the UH-60/Blackhawk housing was developed using 2D drawings from the Army's Engineering Data Information System. This model, shown in Figure 11, serves as the basis for integrating gear geometry and housing dynamics.

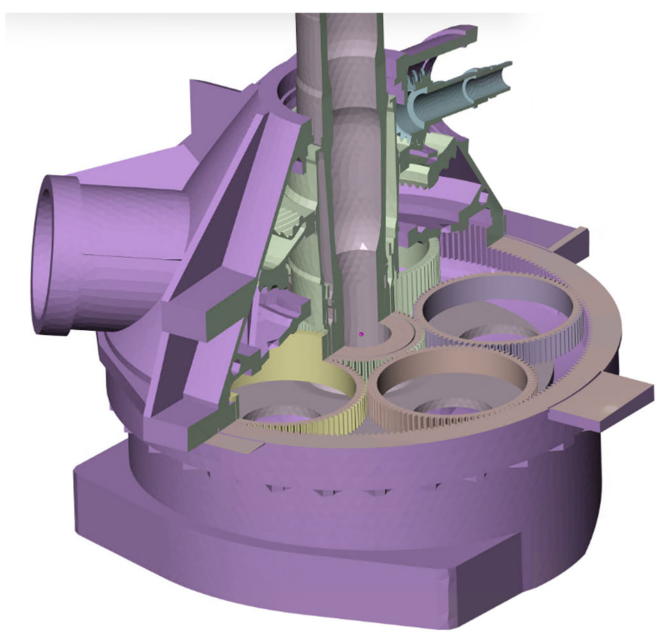

Figure 11. Baseline model of the UH-60/Blackhawk.

The Transmission3D software was used to theoretically generate gear teeth geometry, which was subsequently integrated with the housing using Fourier surfaces. This methodology enables the coupling of damage at the tooth level to the dynamic responses in the housing. By treating each finite element node as a virtual sensor, this approach proves highly effective for studying sensor placement, sensor fusion, and array filtering. Furthermore, it allows for the analysis of both fixed-frame and static-frame sensors.

The modeling of the spur gears for the planet and sun gears was relatively straightforward with 2D drawing parameters, but the input and tail take-off gears required significant effort due to the bevel gear surface geometry. The design process begins with the creation of the bevel gear, followed by the design of the mating pinion. This process simulates the physical cutting of the gear and relies on machine setting parameters and cutter geometry parameters. Typically, this information is available in an ".sba" file used by Gleason to produce the teeth. However, access to the .sba files from Sikorsky was denied, necessitating a back-calculation of the required information.

The methodology of Gonzalez-Perez et al. (2010) was used to determine the basic gear and pinion data, as well as the gear machine settings, based on values from the gear drawings. A synthesis procedure established the pinion machine settings to achieve nearly conjugate motion and proper tooth surface contact. This process was implemented using the Integrated Gear Design (IGD) software for both the input and tail take-off spiral bevel stages. This approach solved a set of nonlinear algebraic equations to ensure continuous surface-to-surface contact and tangency between the gear and pinion throughout the mesh cycle, in accordance with the fundamental law of gearing.

The resulting spiral bevel pair was then analyzed statically in Transmission3D at low load to determine the contact path. As shown in Figures 12 and 13, the load is centered along the tooth surface, with no contact at the tooth edges.

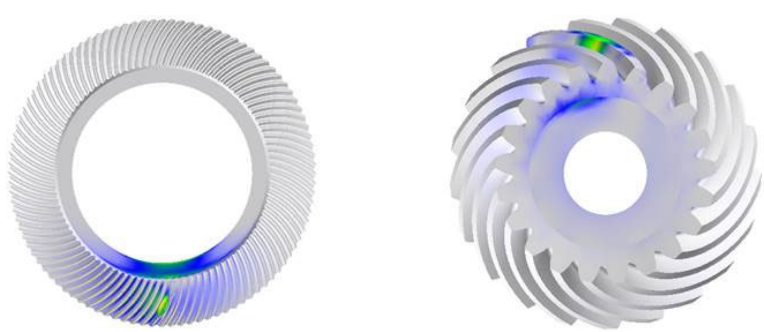

Figure 12. Models of the gear (left) and pinion (right) after synthesis.

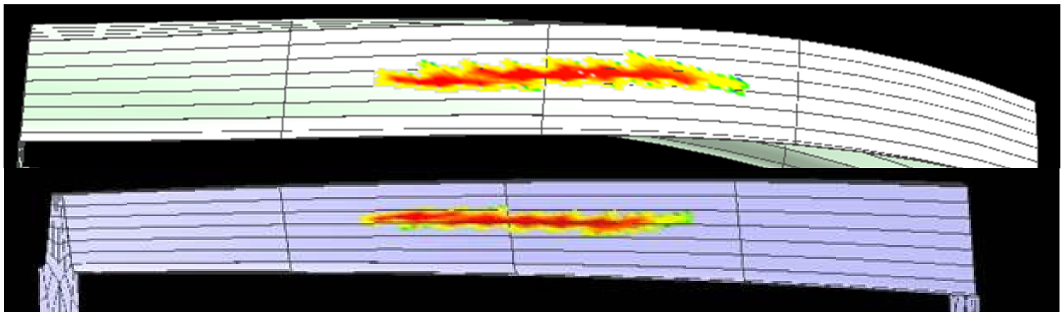

Figure 13. FE/CM calculation of tooth contact pattern for the pinion (top) and synthesized gear (bottom).

Despite the significant progress achieved in developing the UH-60/Blackhawk dynamic model, the integration of the input spiral bevel gears with the housing solid model represents work that remains to be completed. The complexity of spiral bevel geometry, combined with limited access to proprietary manufacturing data, presented challenges that extend beyond the current status. The foundational elements are in place, including validated methodologies for gear generation and housing dynamics, positioning this final integration as a logical next step in future development efforts. Completing this task will enable full-system simulations and unlock the model's complete potential for sensor optimization and diagnostic applications.

4.3 Fault Modes

The initial fault modes chosen for investigation were gear tooth cracks and surface spalls. Both fault modes induce changes in the gear's static transmission error (STE) and mesh stiffness. These changes exhibit strong correlations with the system's vibration, providing valuable insights into fault detection and dynamic behavior. Although dynamic fault behavior has not yet been modeled for the UH-60/Blackhawk, the methodology is established based on previous work. Sample data from a previous study on the OH-58/Kiowa is shown in Figure 14 (Thunuguntla et al. 2025). Gears are modeled with applied torque and resulting stresses as shown in Figure 14a. A gear tooth crack is simulated by disconnecting nodes within the finite element analysis (Figure 14b), and surface defects are simulated by creating voids with an elliptical shape (shown in Figure 14c) at varying heights along the gear tooth face. The corresponding STEs and mesh stiffness values are plotted against the mesh cycle shown in Figure 14d. These variations in displacement and stiffness create vibrations that can be modeled at the housing. The transmission housing's vibration signature can be compared with the experimental data to validate the model.

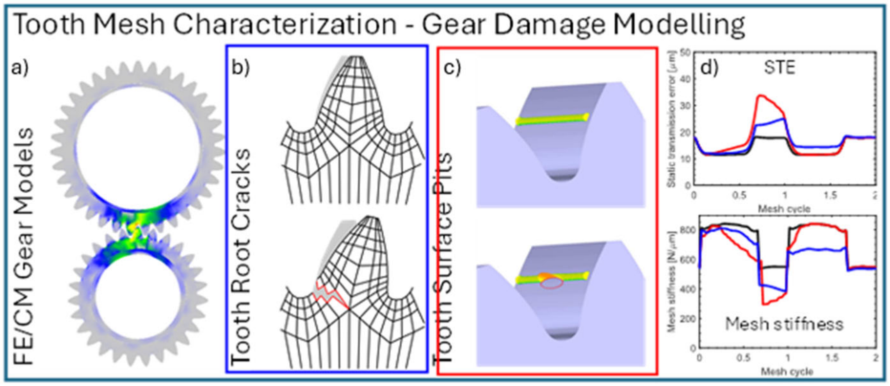

Figure 14. (a–d) Sample data from a previous study that serves as a basis for damaged UH-60 Blackhawk modeling methodology.

5. Future Work and Value to the Army

The following section is an outline of proposed research within PI and its value to the Army.

5.1 Continued Experiments

A validated model will need approximately 10 intercepted transmissions with experimental data paired with a damaged component's failure photographs. These 10 transmissions could be evaluated in 2 years, assuming that VIPER remains operational and a source of funding becomes available to cover full-time equivalent salaries for two engineers and one technician. Additional nominal costs include consumables for VIPER and freight for the MGBs.

Damaged transmission data is valuable to validate the physics-based dynamic model. Damaged data is key because damaged transmission data is not available from health and usage monitoring data. Typically, a transmission is sent to overhaul after it is damaged, and a valuable characterization opportunity is lost. Creating a large repository of damaged transmission data aids ARL's model development, and it could also be shared with industry for similar work.

5.2 Large Data Set Generation

After the model is validated, it will simulate hundreds of damaged transmission cases to build a large repository of training data for AI/ML algorithms. The combination of experimental data, model generated data, and collected field usage data will give a sufficient amount and type of data for model training.

The dynamic physics-based model has additional value because it will be capable of accurately simulating damaged components to support issues seen in the field.

Narrowly focused research efforts to solve issues in the field are expensive to evaluate experimentally. This is why we need the validated dynamic model. The model will be able to generate data for analysis and process algorithms to solve problems in the field.

5.3 Algorithm Development

Determining the most effective AI/ML algorithm will be an iterative process starting with neural network-based, supervised ML algorithms. These algorithms will be developed, trained, and iteratively refined using the generated data from accelerometers and acoustic emission sensors. Ground truth data from intercepted transmissions and actual usage data will be used for final algorithm testing.

The algorithm provides value by showing what is possible in a laboratory environment. Implementation into Army helicopters will require additional input and support along the acquisition chain. The value to Army Aviation and the Soldier occurs through improved readiness and reduced maintenance burdens to support the mission.

5.4 Overhaul Analysis and Continued Partnerships

The overhaul analysis is crucial to PI to obtain the physical characteristics of the faults, but it also provides a valuable opportunity for researchers to engage components of the Army that are closer to the fight. Close collaboration between researchers and overhaul facilities provides value to the Soldier through improved diagnostic algorithms and more strategic placement of existing sensors.

5.5 Cost–Benefit Analysis

A cost–benefit analysis would further strengthen the case for adopting PI within the Army's maintenance program. Although AI algorithms for fault detection have the potential to reduce the Army's maintenance burden, a detailed assessment quantifying the anticipated cost savings—either as a dollar amount or as a percentage of total maintenance costs—has not yet been performed. To ensure comprehensive analysis, we intend to collaborate with a program office partner who has visibility into the maintenance budget, enabling us to clearly demonstrate the value of AI for the maintenance of fielded systems.

6. Conclusion

The groundwork for PI has been laid. Two baseline transmissions and three intercepted transmissions have been run through an experimental test matrix to collect vibration characteristics. A preliminary analysis of the data shows an interesting trend that may improve sensor placement and increase the performance of existing sensors. Modeling the UH-60/Blackhawk transmission is well underway, and one case of damage has been recorded for future damaged model validation. Continuation of PI will enable AI/ML through large data sets to improve rotorcraft transmission diagnostics. PI is currently paused due to funding reallocations. We hope to build off this foundation in the future.

PI sets the stage for a maintenance practice revolution. Integrating AI/ML with modeling, laboratory experiments, and real-world damage dynamics to inform diagnostics could be applied to every critical component's life cycle. Reduced life-cycle costs, increased aircraft availability, and elimination of overly conservative maintenance intervals directly support the Army's operational readiness and sustainment goals.

7. References

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Appendix. Transmission Loan Agreement*

* This appendix appears in its original form, without editorial change.

DEPARTMENT OF THE ARMY

United States Army Aviation and Missile Command
Redstone Arsenal, Alabama 35898-5000

AGREEMENT FOR THE LOAN OF U.S. ARMY MATERIEL (DA FORM 4881)

SUBJECT: Loan Agreement for TRANSMISSION,MECHAN, 1615015427514, 2, EA, Document Number W58H0Z5105C200

1. This loan agreement, in accordance with AR 700-131, is for the loan of materiel by U.S. Army Aviation and Missile Command, ATTN: AMSAM-MSC-SSI, Redstone Arsenal, AL 35898-5200 to DR. RYAN EMERSON, SCMD-UTILITY, AMAM-LS, 5301 SPARKMAN CR. , REDSTONE ARSENAL, AL, 35898. Once the loan agreement has been signed and returned by you, the materiel will be shipped. This loan expires 17 Oct 25.

2. The material is being used to/for the following purpose: The Army Research Lab (Aberdeen Proving Ground, MD) requests two UH60M gearboxes to determine how to improve the predictive indicators for premature failure on UH-60 main mod transmissions. The testing is NONDESTRUCTIVE and will be used for RDT&E, IAW AR700-131, their team will be installing them on a test stand and briefly running them while measuring their "health" signals. The condition/status of the assets will not change. The process will take a total of six weeks (three weeks per gearbox). When they conclude testing, they will coordinate and pay for shipping to DLA Corpus Christi, where they will be getting inducted for rebuild at the Powertrain Production operation at CCAD. The assets will be on consignment at Red River DLA throughout the duration of the loan in LMP and will show as delivered to Army Research Directorate, DEVCOM Army Research Laboratory, BLDG 4603, APG, MD 21005. Once the testing is complete and the assets are shipped and received at the depot in Corpus Christi the loan will be closed and assets removed from consignment. A 309 transfer in LMP will be completed to balance. Loan materiel cannot be used for any other purpose without our express agreement. Equipment may not be modified or altered by the borrower per AR 700-131, chapter 2-1r, unless previously approved by lender.

3. The Certificate of Receipt is provided(encl). Upon receipt of loan materiel, annotate the serial/USA number(s)if applicable and sign the certificate of receipt.This certificate must be returned NLT 30 days from receipt of materiel.

4. The loaned materiel is the property of the U.S. Army Aviation and Missile Command (AMCOM). We will make every effort to see that the materiel is in serviceable and usable condition for the purpose you have indicated, but we make no guarantee or warranty. Loan materiel cannot be shipped or transferred without our permission. According to AR 700-131, the property must be secured, transported, used, and stored with due care and diligence. All expenses and/or liability resulting from its transportation and/or use are your responsibility. Expenses consist of Supply Depot Transportation (SDT), issue/return, and Supply Depot Operations (SDO) for Packaging/Handling. The borrower will safeguard and secure any high value items, any sensitive serial-numbered items and arms. The borrower will prevent misuse of borrowed materiel; or its use by unauthorized persons. The lender will have free access to the loaned materiel for the purpose of inspecting or inventorying.

5. You will not mortgage, pledge, sublet, or part with possession of borrowed materiel in any manner to any third party either directly or indirectly. The materiel must be kept in the same condition in which it was received (unless approved by CECOM item managers or Staff Synchronization Officers). If it is returned in a lesser condition, you may be charged for all the expenses of returning materiel to original received condition.

6. All PBOs will be responsible and compliant with the policy and guidance set forth in the temporary loaning of CECOM-owned and HQDA G8 resourced. The PBO signing the loan agreement will take responsibility for the serial numbered items and load them into a Accountable System of Record (APSR) within 5 working days of receipt. Approved APSRs are GCSS-Army and DPAS. All loaned materiel will be input into an APSR as Property Book Identifier Code 6 (DPAS and GCSS-Army). APSRs will show the recorder and user of the serial

numbered items, thereby providing visual accountability to everyone.

7. This loan is to meet a short-term, non-recurring need. If you have a continuing need for this materiel, you must submit DA Form 4610-R to have it added to your Modification Table of Organization and Equipment/Table of Distribution and Allowances through proper channels to the following address:

U.S. Army Force Management Support Agency
ATTN: MOFI-OPS
5801 20th Street
Fort Belvoir, VA 22060-5578
https://fmsweb.army.mil
(703) 805-1135 (DSN 655)

Refer to AR 71-32 for instructions if necessary. Send us a copy of your paperwork.

8. If you have the materiel longer than one year, you must inventory it for completeness and serviceability and provide us the results in writing. This must be accomplished annually for all loaned equipment. If you request an extension, provide us the results of your inventory and the extension request no later than 45 days prior to expiration.

9. Forward the completed Equipment Inspection and Maintenance Worksheet, DA Form 2404, to us when you are ready to return the materiel. This inspection report will be used as a basis of determining disposition of the materiel. Any costs will be incurred by borrower.

10. Any dispute arising under this loan agreement which we cannot resolve will be decided by the Secretary of the Army or designee.

11. The following signatures are required to validate this loan agreement:

________________________ ____
(Signature of Lender) DATE
Jennifer Barrere
Chief, Supply Operations Branch
Audit Readiness Division
U.S. Army Aviation & Missile Command
ALC Materiel Support Directorate

(Signature of Borrower) DATE
Representative of Borrower
Name: DR. RYAN EMERSON
Title: Accountable Property
Officer
Office Symbol: 5301 SPARKMAN CR.
DSN: 301-802-5428
FAX:

________________________ ____
(Signature of User) DATE
By signing as the user signifies
that you have read the loan
agreement and agree to the terms.

Your loan has been approved. The Loan Agreement and Certificate of Receipt are attached. Please review the Loan Agreement carefully, print, sign (APO and User) and fax signed loan agreement to the fax number provided at the bottom of the Certificate of Receipt. As soon as the materiel has been received, please sign the Certificate of Receipt, annotate Serial Numbers if applicable and fax to the number provided.

CERTIFICATION OF RECEIPT OF LOANED MATERIEL

I certify receipt of and assume responsibility/accountability for the following Army equipment loaned materiel. Any loss/damage to loaned materiel will be subject to AR 735-5:

NSN 1615015427514
DOCUMENT NUMBER W58H0Z5105C200
NOMEN TRANSMISSION,MECHAN
QTY 2 EA

The materiel was received in good condition except as noted (does not negate requirement for submission of SF 361 and/or SF 364, if necessary).

Please annotate Serial Numbers below:

____
USER

____
Signature of Installation
Accountable Property Officer (ACTPO)

DR. RYAN EMERSON
Typed name of ACTPO

Please return this completed form to:

AMCOM
AMAM-LMA-S
Redstone Arsenal, AL 35898-5200
FAX DSN 788-2522, FAX Comm (256)842- 2522

List of Symbols, Abbreviations, and Acronyms

2D	Two-Dimensional
AI	Artificial Intelligence
AMCOM	Aviation and Missile Command
ARL	Army Research Laboratory
CCAD	Corpus Christi Army Depot
CI	Condition Indicator
DEVCOM	U.S. Army Combat Capabilities Development Command
DLA	Defense Logistics Agency
FE/CM	Finite Element/Contact Mechanics
FY	Fiscal Year
IGD	Integrated Gear Design
MGB	Main Gearbox
ML	Machine Learning
NAVAIR	Naval Air Systems Command
PI	Project Interception
PM Utility	Project Manager, Utility Helicopters
RMS	Root Mean Square
SEM	Scanning Electron Microscope
STE	Static Transmission Error
thou	Thousands of an Inch
VIPER	Vehicle Innovative Powertrain Experimental Research

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
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