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William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Summary of U.S. Army Seeded Fault Tests for Helicopter Bearings

February 2016

Final Report

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16. Abstract

The U.S. Army Aviation and Missile Research, Development, and Engineering Center conducts and evaluates airworthiness qualification testing for aircraft and associated components using both aircraft ground test stands and aircraft flying platforms. Recent testing has included seeded fault testing on aircraft components. Seeded fault testing is conducted on the stands and platforms to evaluate the effectiveness of condition-based monitors and associated software algorithms to discern the presence and severity of hardware fault anomalies for aircraft drive train and engine components. A robust and effective Condition Based Maintenance (CBM) system can provide a basis for maintenance and airworthiness credits and debits that modify legacy maintenance practices and intervals. As part of the continuous analysis of CBM data provided by the fielded systems and seeded fault tests, CBM applications to legacy scheduled maintenance intervals for servicing and inspection can enhance current maintenance practices to increase aircraft availability and optimize safe operations and maintenance costs. Similarly, validated CBM data can be used to modify maintenance intervals for affected components, thereby providing an alternate means for maintaining continued airworthiness. In addition, validated CBM systems can be used to transition away from current reactive maintenance practices to a proactive maintenance strategy in a manner that does not adversely impact risk associated with the aircraft's certification. A key to the CBM validation is substantiating that component failure modes are detectable using a system that provides a detection alert to the maintainer at a point that will not result in the failure mode progressing or manifesting into a failed state within specified maintenance intervals using the CBM system. This report documents seeded fault testing on U.S. Army helicopter bearings for validating a CBM system to achieve maintenance credits on legacy flight hardware. The test methodology and requirements used for qualifying CBM system performance is provided to the Federal Aviation Administration under an interagency agreement to promote certification methodology of similar systems on civil aircraft, as appropriate.

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LIST OF ACRONYMS

AC	Advisory Circular
ADS	Aeronautical Design Standard
AE	Acoustic emissions
AED	Aviation Engineering Directorate
AMD	Amplitude demodulated
ARL	Army Research Laboratory
ASIF	Aviation Systems Integration Facility
AFTD	Aviation Flight Test Directorate (formerly the Army Aviation Technical Test Center)
AVA	Aviation Vibration Analyzer
AWR	Airworthiness release
BE	Bearing energy
CBM	Condition-based maintenance
CC	Condition Change
CCAD	Corpus Christi Army Depot
CDD	Capabilities Development Document
CI	Condition indicator
CRT	Component Retirement Time
CSI	Critical Safety Item
DA	Department of the Army
DAQ	Data acquisition system
DBE	Dual-band energy
DSC	Data Source Collector
FAA	Federal Aviation Administration
FHA	Functional Hazard Assessment
GBS	Ground-based station
GSA	U.S. General Services Administration
HUMS	Health Usage Monitoring System
HI	Health indicator
IAC	Intelligence Automation Corporation
IGB	Intermediate gearbox
IPS	Inches per second
IPT	Integrated Product Team
MG	Miscellaneous Guidance
MRSP	Main rotor swashplate
MSPU	Modern Signal Processing Unit
MTBR	Mean time between removal
O&S	Operation and support
OEM	Original equipment manufacturer
QDR	Quality Deficiency Report
PMI	Preventive Maintenance Inspection
PMO	Program Manager's Office
PMS	Preventive Maintenance Service
P/N	Part number

RC	Retirement Change
RCM	Reliability-centered maintenance
RIMFIRE	Reliability Improvement through Failure Identification and Reporting
RPM	Revolutions per minute
RTC	Redstone Test Center
SCNG	South Carolina National Guard
S/N	Serial number
SOW	Statement of Work
TBO	Time between overhaul
TC	Time change
TDA	Teardown analysis
TRDS	Tail rotor driveshaft
TRGB	Tail rotor gear box
TRDT	Tail rotor drive train
TRR	Test Readiness Review
USC	University of South Carolina
UUT	Unit under test
V&V	Verification and validation
VMEP	Vibration Management Enhancement Program

EXECUTIVE SUMMARY

The U.S. Army has been actively pursuing condition-based maintenance (CBM) for over a decade. To leverage CBM knowledge between government agencies, the Federal Aviation Administration (FAA) contracted with the U.S. Army to obtain real world examples of CBM-seeded fault testing. The purpose of this report is to inform the FAA of the activities and methods being used by the U.S. Army to substantiate CBM practices.

Specifically, the U.S. Army Aviation Engineering Directorate is providing documentation of seeded fault testing methods and examples of how it is collecting evidence and its findings to date. The documentation includes direct and indirect evidence and test programs with Health Usage Monitoring System equipment for the seeded fault tests.

This documentation also includes evidence developed from teardown analysis and inspections. The methods for using seeded fault tests and teardown analysis data to substantiate maintenance, including usage credits, are included.

1. INTRODUCTION

The objective of this document is to present the methodologies and emphasize the necessity of the seeded fault testing that the U.S. Army has used in pursuit of condition-based maintenance (CBM) for a helicopter tail rotor driveshaft (TRDS) hanger bearing and main rotor swashplate (MRSP) bearing. This report outlines the seeded fault testing applications and how the applications facilitate Health Usage Monitoring System (HUMS) validation for these two components. By providing the Federal Aviation Administration (FAA) with examples of how the U.S. Army addresses seeded fault testing, the agency will be able to improve its Advisory Circulars (ACs) and regulations and provide civil aviation with additional methodologies to implement usage based credits.

2. BACKGROUND

U.S. Army Aviation has been performing preventive and reactive maintenance on legacy rotorcraft drive system and dynamic components for decades. When CBM came to the maintenance forefront, the proactive CBM maintenance practices had to account for the rationale behind an existing U.S. Army helicopter parts' legacy maintenance. This section outlines how the U.S. Army helicopter TRDS hanger bearing and MRSP bearing function, how they are maintained with legacy maintenance, and the intent regarding how they should be maintained to achieve reliability-centered maintenance (RCM) goals once CBM is in effect.

2.1 COMPONENT DESIGN, OPERATION, AND MAINTENANCE

The MRSP bearing and TRDS hanger bearing discussed in this report are both from one specific U.S. Army helicopter model. These are both mechanically simple components that are critical to aircraft control. If the MRSP bearing fails, there is a degradation of control capability in transmitting the cyclic and collective inputs to the main rotor pitch links [1]. The TRDS hanger bearings support the tail rotor drive shafting that transfers the drive torque to the tail rotor. If the hanger bearings fail, then the tail rotor would cease to turn, and the pilot would lose anti-torque and directional control of the aircraft [1].

2.1.1 MRSP

The MRSP is mounted on the static mast between the mixer assembly and main rotor head assembly. The purpose of the swashplate assembly is to transfer control inputs received from the collective and cyclic control sticks in the cockpit into main rotor rotational and pitch control motions. The MRSP installation is shown in figure 1.

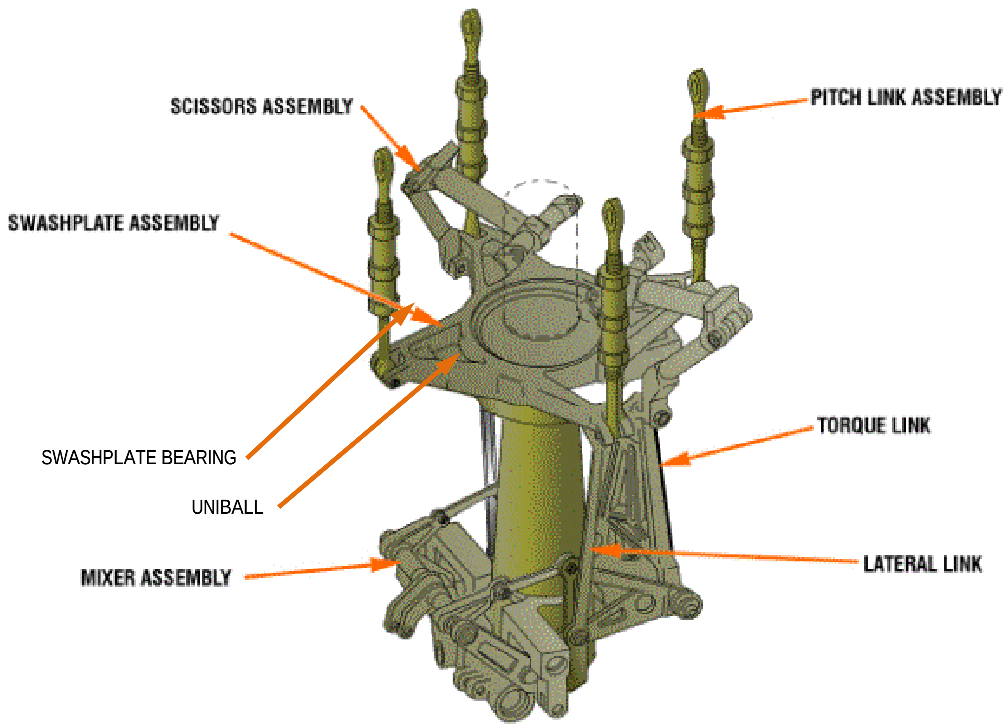


Figure 1. MRSP installation on the main rotor mast

The major components of this particular MRSP assembly are the stationary swashplate, bearing assembly, spherical slider ball (uniball), and rotating swashplate, as shown in figure 2. The MRSP is considered a Critical Safety Item (CSI) for the U.S. Army. A U.S. Army Safety of Flight message removed the MRSP assembly Retirement Change (RC) life and placed the assembly on-condition with a Condition Change (CC) life; however, the MRSP incorporates subcomponents with RC lives discussed in this section.

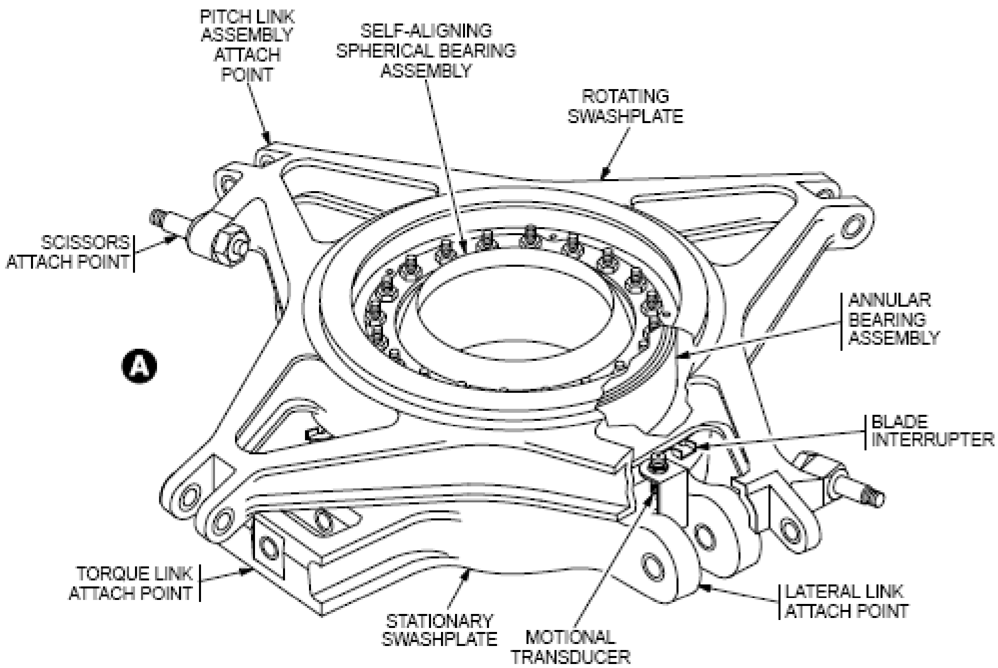


Figure 2. Major components of the MRSP

The stationary swashplate supports the swashplate assembly and receives control inputs from two lateral links and a torque link. It is mounted to the double-row ball bearing below the rotating swashplate. The stationary swashplate houses a self-aligning spherical and slider bearing (uniball). The stationary swashplate is a CSI based on a 7149-T73 Al forging, with heat treatment, hardness, conductivity, and discoloration inspection as the critical characteristics. The assembly has a 12,909 flight hour RC life.

The bearing assembly is located in the center of the swashplate between the stationary and rotating swashplate assemblies. The bearing is a synthetic-grease-lubricated sealed unit. The purpose of the swashplate bearing is to allow for rotation of the main rotor mast while supporting the rotating swashplate controls for all main rotor flight control load inputs. Abnormal discharge of grease (any accumulation in excess of surface film) from the upper or lower bearing seal after 25 hours of operation requires replacement of the swashplate; otherwise, there are no maintenance requirements to replace the MRSP bearing grease between overhauls. Figure 3 shows the bearing assembly installation in the MRSP. The bearing is a one-piece outer race and three-piece inner race with flexible and removable upper and lower seals.

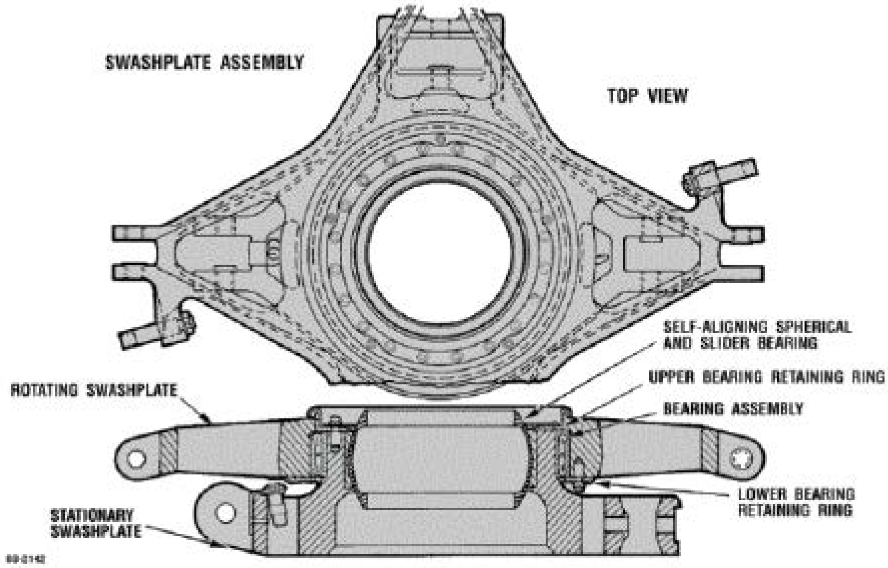


Figure 3. Bearing assembly and uniball installation in MRSP

The stationary swashplate attaches to the inner race of the bearing assembly, and the rotating swashplate attaches to the outer race of the ball bearing assembly. There are two rows of balls (upper and lower) with wire cages each incorporating 86 ball bearings. The ball and raceway material is 52100 Consumable Electrode Vacuum Melted steel. The bearing assembly is also considered a CSI, with the hardness of the ball and races as the critical characteristics. The bearing assembly has a 2250 flight hour retirement life based on fleet sampling [2]. An analysis of the bearing assembly was conducted for the bearing with Mobilith 220 grease as the lubricant. The bearings must be removed at 2250 flight hours because of a time-based grease life criterion which uses five years as a basis. However, without the grease life criterion, the analytical L10 life yields 15,372 theoretical hours. An L10 life is defined as the life of an anti-friction bearing that is the minimum expected life, in hours, of 90% of a group of bearings that are operated at a given speed, temperature range, and loading with the applicable lubricant.

The spherical slider bearing has two functions. First, it allows the swashplate assembly to tilt for cyclic control movements. Second, it allows the entire MRSP to move up or down the static mast as a unit in response to collective control movements. The spherical ball and outer race material is 7075-T6 aluminum alloy; the spherical ball surface is chrome plated. The outer race and slider portion of the spherical ball incorporate self-lubricating bearing liners of Kapton-type B material.

The rotating swashplate transmits control inputs received from the stationary swashplate to the main rotor blades through the pitch links. The maximum pitch link lug design loads are shown in table 1. The four pitch link assemblies attach to the clevis lugs spaced 90 degrees apart on the rotating swashplate. Two of the clevis lugs, spaced 180 degrees apart, also allow for attachment of two scissor link assemblies. The scissor link assemblies drive the rotating swashplate from the main rotor head at a speed of 292 revolutions per minute (RPM). The rotating swashplate is an aluminum forging that attaches to the outer ring of the double-row ball bearing assembly. It is a CSI based on a 7149-T73 aluminum forging, with heat treatment, hardness, conductivity, and a discoloration inspection as the critical characteristics. The rotating swashplate assembly maintenance is on-condition, with no overhaul interval or retirement life.

Table 1. Pitch link lug loads

Max Load	+1617 lb.
Min Load	- 4640 lb.
Max GAG Cyclic Load	+/- 3129 lb.

GAG = ground air ground

The U.S. Army intends to address RCM goals through the introduction of CBM component monitoring of the MRSP for future maintenance practices. The current CBM monitoring package currently installed on over 98% of fielded aircraft includes a Modern Signal Processing Unit (MSPU). The MSPU sensor installation on the MRSP consists of a single accelerometer (ACCEL #7) and cable mounted in a cavity just behind the stationary swashplate's left lateral link, as shown in figures 4 and 5.

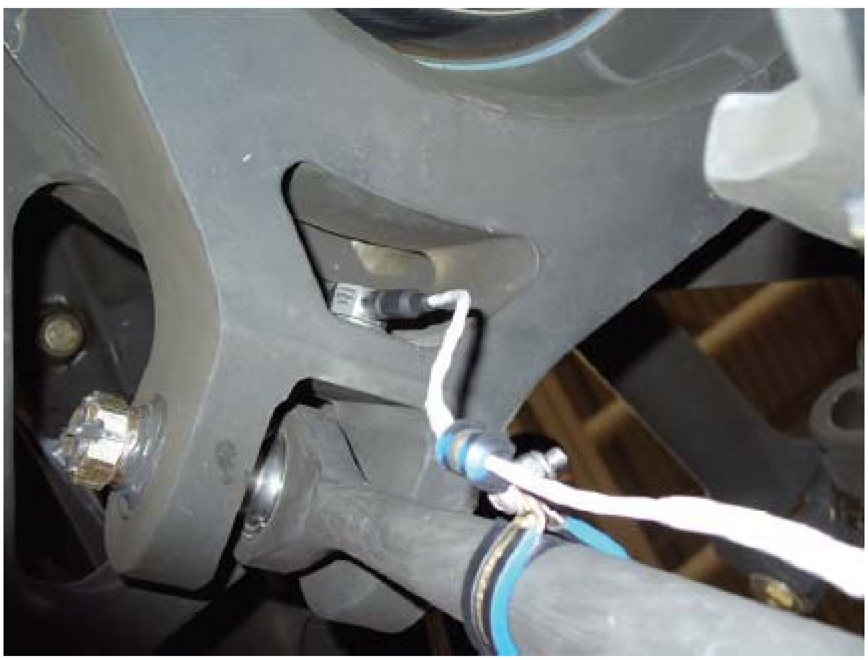


Figure 4. MSPU accelerometer installation on MRSP (looking up)

Figure 5. MSPU accelerometer cable routing on MRSP

The main rotor tachometer signal (TAC-1) on the University of South Carolina (USC) test stand is obtained by a tachometer sensor and existing interrupters mounted on the rotating swashplate's housing, as shown in figures 6a and 6b, respectively.

(a) (b)

Figure 6. The (a) tachometer sensor location and (b) interrupter striker

2.1.2 TRDS

The TRDS assembly is mounted on the helicopter longitudinally atop the tail boom assembly, between the main transmission and intermediate gearbox (IGB) assemblies. The purpose of the TRDS assembly is to transfer main transmission torque via drive shafts to the IGB, tail rotor gearbox (TRGB), and tail rotor blades. The TRDS installation is shown in figure 7.

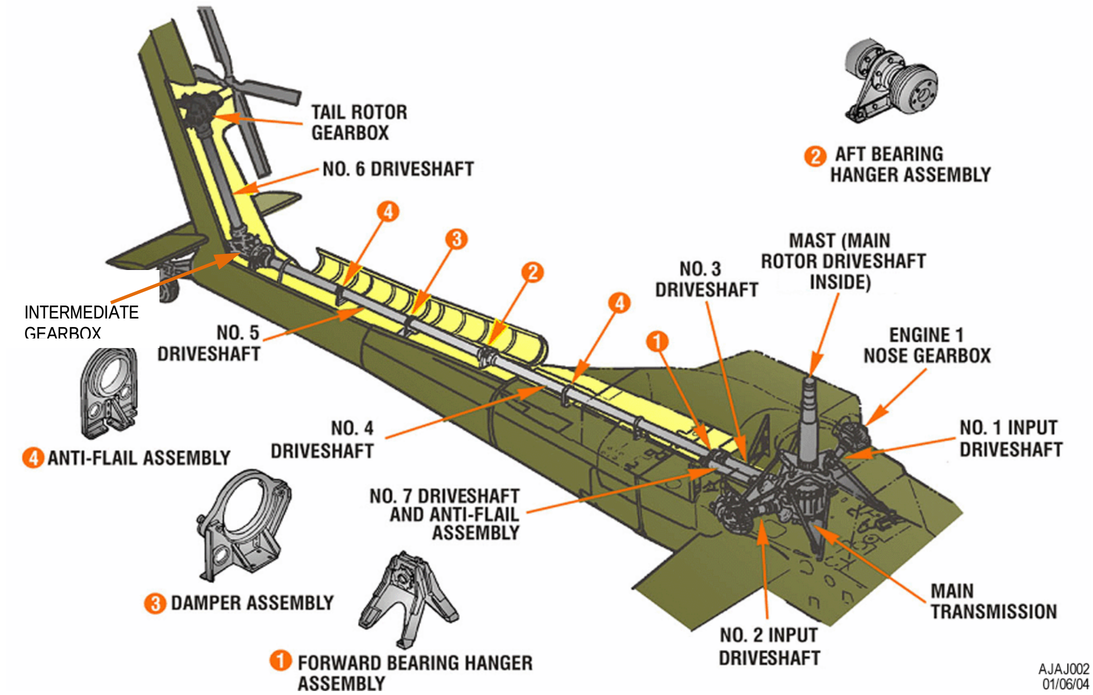


Figure 7. TRDS component installation

The major TRDS assembly components associated with the TRDS hanger bearings are the three drive shafts (see figure 7, drive shafts 3, 4, and 5) and two couplings connected to the two hanger bearing assemblies (see figure 7, bearings #1 and 2). The TRDS hanger bearing flanges have an RC life of 6487 flight hours. These components also incorporate subcomponents with CC inspections.

The common TRDSs in the tail boom have no fatigue life limits and are removed on condition. They are CSIs with balancing and structural integrity as critical characteristics. Structural integrity is ensured with a five-second static test on the drive shafts along with visual and dimensional inspections.

The TRDS couplings connect the individual drive shafts together to transfer the tail rotor torque from the main transmission to the IGB. The couplings are CSIs based on the balancing and structural integrity as critical characteristics. Structural integrity is ensured with a five-second static test on the drive shafts along with a visual and dimensional inspection. A maximum imbalance of 0.07 ounce-inch is the balance requirement. The coupling assemblies have no fatigue life limits and are removed on-condition from inspection.

The hanger bearing assemblies (forward & aft) depicted in figures 8 and 9 are located between drive shaft numbers 3 and 4 and numbers 4 and 5 (see figure 7) of the TRDS. The purposes of the hanger bearings are to couple and support the drive shafts leading from the main transmission out to the IGB. In addition, the hanger bearings allow the transfer of rotational torque through the TRDSs to the IGB. The TRDS hanger bearings are contained within a self-aligning housing. The forward and aft bearings are a single row of nine balls 0.5″ in diameter. The bearings are sealed and filled with MIL-PRF-81322 grease (Mobil 28, Aeroshell 22/22CF, Braycote 622, AROLUBE 81322, GN-22, or ROYCO 22CF) and do not require servicing in the field. The bearings must be removed to be overhauled or disposed of at 2750 flight hours because of grease life criteria. Bearings sent to overhaul can be reclaimed by packing 9.6 cubic centimeters of grease into the bearing following inspection.

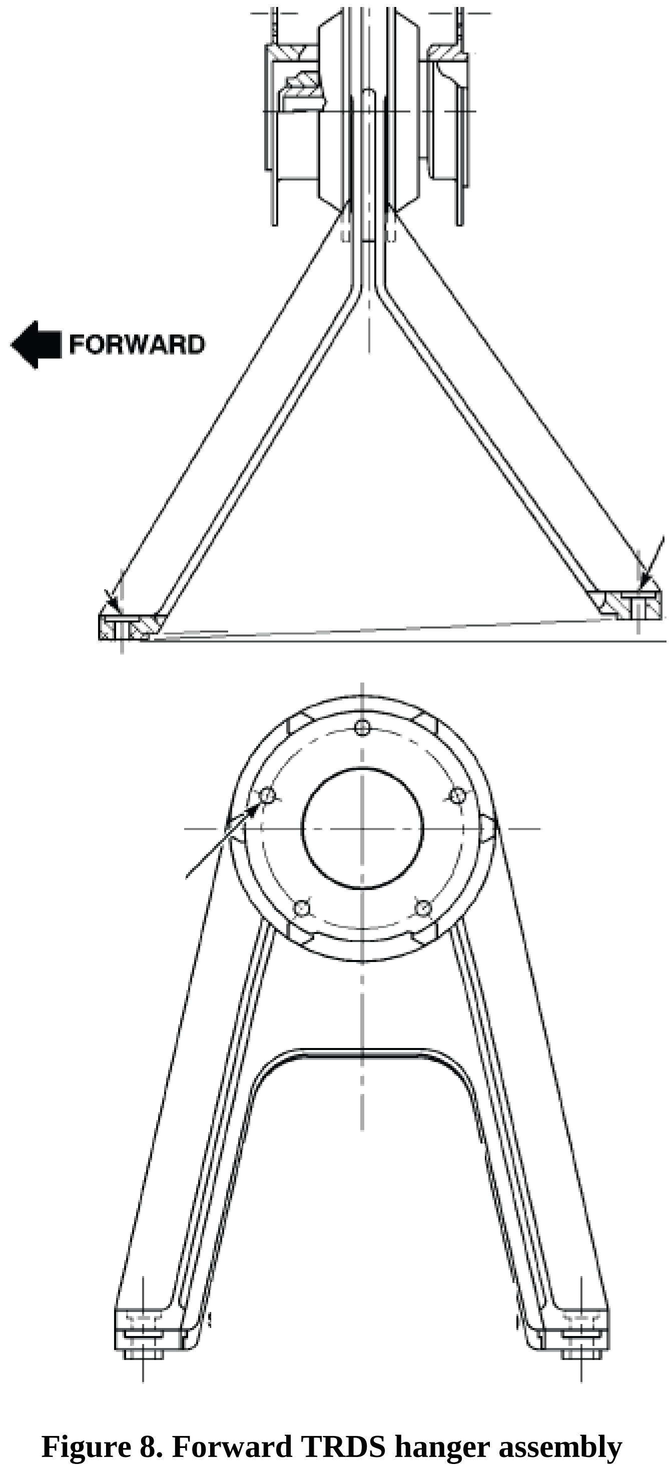


Figure 8. Forward TRDS hanger assembly

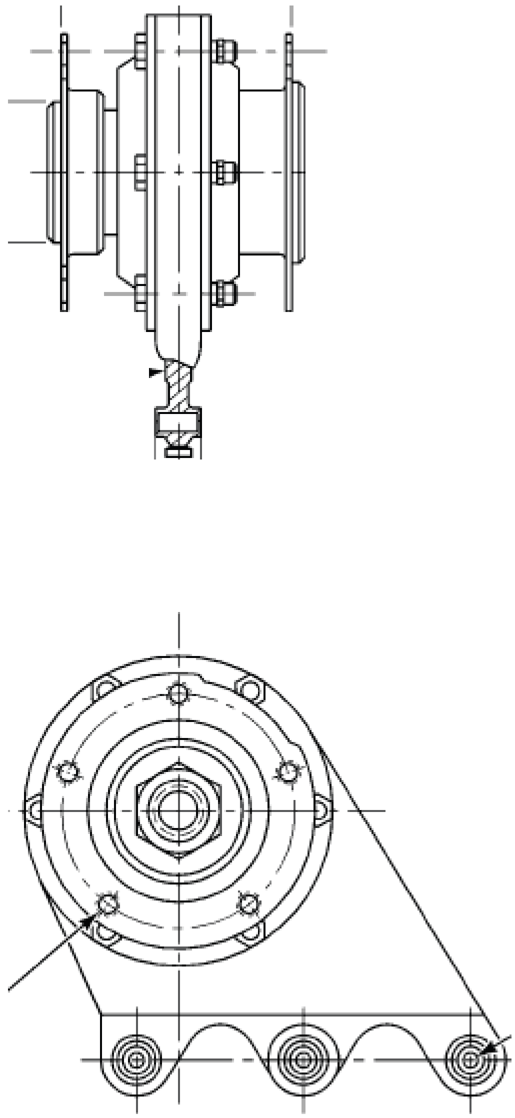


Figure 9. Aft hanger assembly

The TRDS hanger bearings are CSIs and are part of the hanger assembly that aligns the TRDS. Balancing, structural integrity, and proper assembly are critical characteristics. Structural integrity is ensured through inspection, dimensional checks, and a five-second static test on the assembly. The assembly's critical characteristics are to ensure a torque nutation of 10–100 inch-pounds of the bearing within the assembly housing; torque of the mounting flange, self-locking nuts between 700 and 800 inch-pounds above running torque; and a dynamic balance of the flanges to 0.007 ounce-inch or better. The bearings are rated for a rotational speed of 4815 RPM and torque of 4320 in-lb. The hanger bearing assembly can compensate for an angular misalignment of ±2 degrees. The aft hanger bearing assembly weighs 7.35 lb and the forward hanger bearing assembly weighs 9.95 lb.

Like the MRSP, the U.S. Army also desires future maintenance modifications on the TRDS bearings to address intended RCM goals through the introduction of CBM component monitoring. The current CBM monitoring package installed on the TRDS bearings consists of single accelerometers (ACCEL #11 and 12). Each is cable mounted, as shown in figure 10. The TRDS hanger bearing accelerometers are oriented on the hanger bearing radius and attached to the retainer bracket on the starboard side. This applies to both the forward and aft hanger bearings.

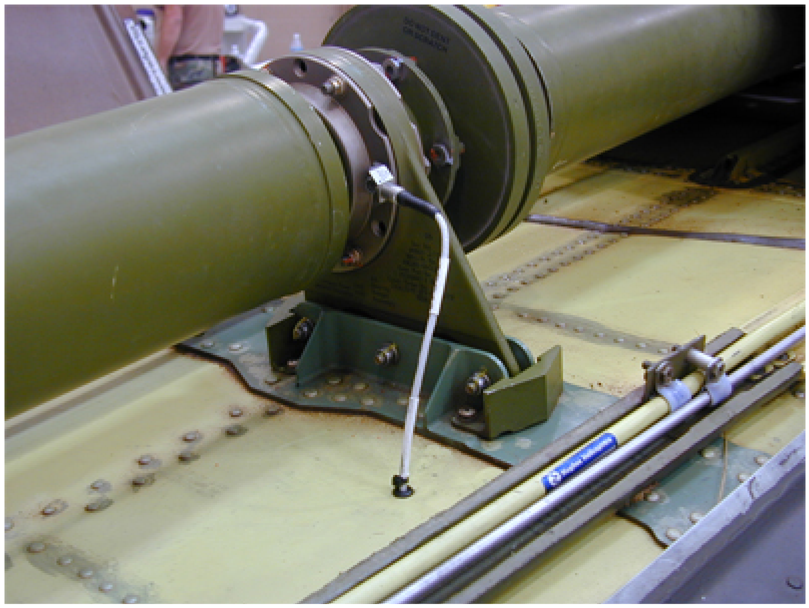


Figure 10. Location of accelerometer on aft hanger bearing

2.2 HISTORICAL MAINTENANCE PRACTICES

Prior to considering CBM enhancements, modifications, or replacements to legacy rotorcraft maintenance using HUMS, it is important to understand what initial specification design, maintenance, and reliability requirements were placed on the legacy helicopter components as well as the engineering rigor used to verify, validate, and establish legacy maintenance practices. Consequently, any maintenance modification or replacement should be verified and validated to be as good as, or better than, legacy maintenance practices. For U.S. Army rotorcraft dynamic components and drive systems, this involves reevaluation of the following:

- User requirements for aircraft usage, maintenance, and reliability
- Bearing L10 analyses
- Bearing endurance testing
- Lubrication shelf life
- Component structural life testing
- Wear rate analyses
- Component reparability
- Specifications used for the original maintenance establishment

Any maintenance change or system implemented to modify or replace legacy maintenance practices should undergo similar analytical and testing rigor to that of legacy maintenance.

For this U.S. Army helicopter MRSP bearing, the following characteristics and maintenance apply:

- Usage = (Hours x 100) hours per year stateside/(2.5 hours x 100) hours per year in theater.

- Maximum Allowed Main Rotor Imbalance in the Field in Flight = 0.2 inches per second (IPS) lateral in hover & 0.3 IPS vertical in forward flight.

- Maintenance (phase and time between overhauls [TBOs]) = Preventive Maintenance Service (PMS) is performed every 25 hours from flight or 14 days (whichever comes first) to visually inspect for cracks, corrosion, mounting security, smooth rotation, grease leakage, and security of lower seal. A 50 flight-hour check for dial indication and feel for roughness/binding; Preventive Maintenance Inspection (PMI) performed every 250 flight hours; a 500 hour phase inspection. TBO is at 2250 hours.

- RC = 2250 flight hours on ball bearing.

- L10 Life = 4500 hours required based on operation at 71% of associated gearbox power rating via specification. Analysis yielded 15,372 hours without accounting for material and lubrication factors which typically increase this probabilistic life.

- Endurance Run out testing = 200-hour bench test, 200-hour military qualification test, 50-hour overspeed, 1250-hour reliability/maintainability test, aircraft flight envelope testing.

- Loss of Lubrication testing = Demonstrates a 30-minute grease out capability.

- Lubricant Shelf Life = Five-year grease life for MIL-G-81322, as specified by Exxon Mobil Corporation.

- Applicable component structural life using Safe Life Approach = MRSP fatigue life of 12,909 flight hours.

- Mean time between removal (MTBR) = 1500 hours.

- Functional Hazard Assessment (FHA) = Spalling and Thermal Runaway as induced by loss of lubrication, corrosion, temperature degraded grease, sand/dust contamination, or salt water contamination. Sheared or seized tail rotor shaft would result in loss of aircraft anti-torque. This could result in crew being unable to control aircraft and continue safe flight, possibly leading to loss of crew and aircraft.

- Specifications = DRC-S-H10000B helicopter system specification, Aeronautical Design Standard (ADS)-50-PRF ADS for Rotorcraft Propulsion Performance and Qualification Requirements.

For these U.S. Army helicopter TRDS hanger bearings, the following characteristics and maintenance apply:

- Usage = (Hours x 100) hours per year stateside/(2.5 hours x 100) hours per year in theater.

- Maximum Allowed Tail Rotor Shaft Imbalance in the Field = 1 IPS on the ground.

- Maintenance (phase and TBO) = PMS is performed every 25 hours from first flight of a mission day or 14 days (whichever comes first) to check for cracks, corrosion, mounting security, smooth rotation, and mounting nut torque stripes. PMI performed every 250 flight hours, requiring a nutation check for angular movement of the bearing off its center axis.

- Time Change = 3250 hours (was 2750 hours based on a maximum operations tempo of [2.5 Hours x 100] hours per year for five years at which point the five-year grease life was accrued. Seeded Fault testing discussed below substantiated going to 3250 hours).

- L10 Life = 4500 hours required and is based on operation at 71% of associated gearbox power rating via specification. Analysis yielded >100,000 hours without accounting for material and lubrication factors which typically increase the probabilistic life.

- Endurance Runout testing = 200-hour bench test, 200-hour military qualification test, 50-hour overspeed, 1250-hour reliability/maintainability test, aircraft flight envelope testing.

- Loss of Lubrication testing = Demonstrates a 30-minute grease out capability 2X.

- Lubricant Shelf Life = Five-year grease life for MIL-PRF-81322, as specified by Exxon Mobil Corporation.

- Applicable component structural life using Safe Life Approach = Input/output bearing flange fatigue life of 6487 flight hours.

- MTBR = 1500 flight hour requirement.

- FHA = Spalling and thermal runaway, as induced by loss of lubrication, corrosion, temperature degraded grease, sand/dust contamination, or salt water contamination. Sheared or seized tail rotor shaft would result in loss of aircraft anti-torque. This could result in crew being unable to control aircraft and continue safe flight, possibly leading to loss of crew and aircraft.

- Specifications = DRC-S-H10000B helicopter system specification; ASTM D3336 Standard Test Method for Life of Lubricating Greases in Ball Bearings at Elevated Temperatures; ADS-50-PRF ADS for Rotorcraft Propulsion Performance and Qualification Requirements; ISO 12103-1 International Standard for Test Dust for Filter Evaluation.

2.2.1 User Requirements

U.S. Army rotorcraft user requirements are published in a Capabilities Development Document (CDD). The helicopter platform Program Manager's Office (PMO) was responsible for developing a Statement of Work (SOW) and system specifications, which addresses maintainability and reliability logistical requirements, among other categories. The Boeing Company, the contracted vendor, then assigned the government maintainability and reliability requirements to the respective subsystems and individual components during aircraft design and development.

For example, this U.S. Army Helicopter's CDD has a requirement for phased maintenance. The helicopter's system specification and SOW then incorporated MTBR requirements of 1500–3000 aircraft operating hours for major dynamic components and a phased maintenance plan under the logistics support analysis. The helicopter's original equipment manufacturer (OEM) then developed hardware designs to ensure operation without a scheduled inspection until a phased maintenance interval. During development of the aircraft, the TRDS hanger bearings and MRSP bearing were subsequently tested and analyzed to ensure they would be capable of operation without inspection until an inspection/service or overhaul interval was performed. Because these were legacy designs, CBM intervals were not originally designed into the components because this was not a specified requirement from the user through the PM to the vendor. Therefore, continued airworthiness was ensured in the components through field inspections, component retirements, and depot overhaul intervals.

2.2.2 U.S. Army Qualification Requirements

For drive system and dynamic component basic design and qualification testing requirements, the U.S. Army uses ADS 50 [3]. These requirements were flowed to the contractor via the SOW and system specifications to ensure the vendor designs met standard military qualification tests for safety and performance.

These design and qualification standards require vendors to incorporate minimum L10 lives for bearings; incorporate minimum design life limits in the realm of thousands of hours or cycles; and demonstrate performance capabilities through analysis and thousands of hours of endurance tests.

The qualification requirements for this U.S. Army Helicopter's hanger bearings and MRSP bearing include:

- Analysis demonstrating minimum L10 life of 4500 hours based on operation at 71% of associated gearbox drive shaft power rating

- Conducting a bearing temperature survey with the gearbox operated at input loads of up to 120% gearbox power rating and at speeds up to the maximum speed allowed by the aircraft specification and within the design allowables for bearing temperature

- Demonstration of a self-aligning feature should be provided for the bearing component of each TRDS hanger bearing assembly

- Demonstration for checking and servicing drive shaft grease lubricated bearings

- Demonstration of ability to operate without failure at the maximum allowable shaft misalignment

- For first time design, a 200-hour overstress bench test followed by a tear down inspection; 200-hour military qualification test on the propulsion system test bed; 50-hour overspeed test runs at 30 seconds, plus 3 seconds at 120% of normal rated speed on the propulsion system test bed; 1250-hour reliability/maintainability test on the propulsion system test bed consisting of a composite of the mission profiles for the aircraft; and fatigue test of two specimens

- For new source vendor qualification, a 200-hour endurance bench test and metallurgical inspection (two specimens required for MRSP)

Currently, there are few HUMS specification requirements for conducting CBM on U.S. Army aircraft. As a result, the U.S. Army developed the ADS 79 Handbook [4] to facilitate informing U.S. Army agencies and the commercial aviation industry of the Aviation Engineering Directorate (AED) guidelines and practices for CBM safety and performance to achieve qualification status.

In addition to the ADS 79 guidelines, designers and maintainers must be cognizant of other factors that affect safety and performance limits for legacy rotorcraft. For example, lubricant shelf life and component reparability limits must be considered when establishing inspection and overhaul intervals.

The qualification and specification requirements for both HUMS and legacy rotorcraft emphasizes the fact that current inspections and overhaul intervals are in place based on the knowledge attained from a multitude of variables through analyses and thousands of test hours. Consequently, any CBM system proposed to replace or modify legacy inspections and overhaul intervals should undergo similar scrutiny to demonstrate sufficient engineering rigor and robust design. Though this facilitates substantiating safe performance and reduces liability exposure, it is a source of great contention when confronted with increased costs and schedules to implement a new maintenance philosophy. However, these factors should be considered up front in an RCM analysis prior to selecting a new maintenance system [5–7].

In contrast, any CBM system proposed to enhance legacy inspections through the addition of sensors need only demonstrate an acceptable minimal level of false alerts to those maintaining the aircraft and funding the operation and support (O&S) costs. The legacy maintenance is already capturing the required support activities necessary to ensure baseline risk.

2.3 DEPARTMENT OF THE ARMY FORM 2410 HISTORY

Department of the Army (DA) Form 2410 (see figure 11) is the documentary backbone of the system the U.S. Army uses to track component operating time and discern why many of the components are being removed. This system requires the maintainer to document the reason for removal and the amount of time the component was used for all time tracked. This system is used to create a database highlighting problems and trends inside the various aircraft fleets and enables engineers to see which parts achieve the end of their designed useful life. In addition, engineers may view which parts are returned the most often prior to achieving their designed useful life, allowing the engineers to focus on developing solutions to lessen the increased maintenance burdens for premature removals.

COMPONENT REMOVAL AND REPAIR/OVERHAUL RECORD For use of this form, see DA PAM 738-751; the proponent agency is DCSLOG	*REQUIREMENT CONTROL SYMBOL* *CSGLD-1052(R3)*

SECTION I - IDENTIFICATION

CONTROL NUMBER	1. NOMENCLATURE	2. NSN	3. PART NUMBER
624882	Engine Gas Turbine	2840-01-070-1003	6035T00G01

4. SERIAL NUMBER	5. CAGE CODE	6. NO. OF PREV O/Hs	7. TIME SINCE LAST INST *(HRS)*	8. TIME SINCE NEW *(HRS)*	9. TIME SINCE OVERHAUL *(HRS)*	10. FAILURE CODE
GEE3065[redacted]	99207	CC	~~350~~ 0	~~2766~~ 2769	CC	~~317~~ 799

11. POS	12. HSF	13. METER HRS	14. WUC	16. APU SSN	17. APU HRS	18. APU SSO	19. VERSION
1			04A				

15. COMPONENT CUMULATIVE COUNT/HOURS			
a. LCF 1	b. LCF 2	c. TTI	d. OP HOURS
1049	7323	830	2769
~~1047~~	~~7317~~	~~818~~	~~2766~~

SECTION III - REPAIR/OVERHAUL/GAIN

20. REMOVED FROM *(NOMEN NHA)*	21. NSN *(NHA)*	22. PART NUMBER *(NHA)*

23. SERIAL NUMBER *(NHA)*	24. HOURS *(NHA)*	26. APU START METER	27. APU HOUR METER
	1385		

25. NHA CUMULATIVE COUNT/HOURS			
a. LCF 1	b. LCF 2	c. TTI	d. OP HOURS

28. HISTORY RECORDER SN
ECD03595

29. HISTORY RECORDER READING			
a. LCF 1	b. LCF 2	c. TTI	d. OP HOURS
274	1603	147	685
~~272~~	~~1597~~	~~135~~	~~682~~

30. ACFT MODEL	31. ACFT S/N	32. MAINT LEVEL	33. DATE REMOVED	34. UIC *(This Action)*
UH-60A	802342[redacted]	O	96128	WOWFAA

39. DATE CHECKED	40. PID AND TELEPHONE NUMBER	41. UIC *(This Action)*	42. MANHOURS TO REPAIR/OVERHAUL
96185	AW0980 DSN 861-2361	WOMUAA	203

43. INSPECTION AND ACTION CODES						44. REASON FOR GAIN	45. CONTRACT NUMBER	46. MAINT LEVEL	47. ACT FAIL CODE	48. SRA/ESRA
	(A) SERV		E	(E) REPAIR	(G) REBUILT			D	317	N
	(B) UNSERV	(D) REMFG		(F) O/HAUL						

REMARKS

Total cumulative counts and hours calculated by WOWFAA due to history recorder failure.

DA FORM 2410, OCT 97 DA FORM 2410, JAN 92, IS OBSOLETE **REPAIR/OVERHAUL/GAIN COPY 2**

Figure 11. DA Form 2410 example

There are some inherent flaws with the DA Form 2410 system that come primarily from the human element. There are numerous failure code options (figure 11, block 10) to describe a component failure. It is often difficult for maintainers to accurately match one of the many failure code options to the actual component fault. This sometimes results in a maintainer entering a failure code that is convenient or expedient to complete the paperwork on a component and return to performing the necessary mechanical work to get the aircraft operational. In addition, field maintainers are not authorized to disassemble most transmissions when an oil debris sensor/chip detector alert is activated. The failure code for these scenarios is then documented as a chip light without the conduct of a teardown analysis to discover the exact item failing within a transmission. As a result, the DA Form 2410 database contains inaccurate information that must be carefully analyzed prior to developing conclusions and recommendations.

A review of 2410 data from January 1, 2009–June 19, 2011 found several hundred MRSP removals, with over a quarter of those as chargeable removals (removal based on an actual fault). The MTBR for the bearing averages 1767 hours over the last 10 years. The top four field removal causes for the MRSP were “bearing or bushing failure;” “worn excessively;” “beyond specified tolerance;” and “binding-friction excessive.” A more complete list is shown in table 2 (the fault codes usually responsible for bearing faults are shaded). Note that although the MRSP incorporates a bearing assembly and several bushings, the specific bearing, bushing, or other subcomponent is often not cited in the DA Form 2410 and database.

Table 2. DA Form 2410 logged faults for the MRSP assembly over 29.5 months

Logged Fault	Percent of Failures
Bearing or Bushing Failure	36%
Worn Excessively	9%
Beyond Specified Tolerance	7%
Binding-Friction Excessive	5%
Broken	4%
Dented	4%
Blistered	4%
Vibration Excessive	3%
Grooved	3%
Leaking Liquid	3%
Corroded	2%
Torn	2%
Pitted	2%
Mechanical Binding	1%
Contact/Connection Defective	1%
Flaking	1%
Fails Diagnostic	1%
Burned/Includes Charred	1%
Deteriorated	1%
Chafed	1%
Burred	1%
Cracked	1%
Faulty Reading	1%
Improperly installed	1%
Seal/Gasket Blown	1%
Brush Failure/Worn Excessively	1%
Accident Damage	1%
Stripped	1%
Lightning Strike	1%
Grand Total Percent	100%

The DA Form 2410 data for this helicopter hanger bearing in 2010 (see table 3) shows several hundred removals. Of the total removals, the top-five field removal causes for the hanger bearings were “bearing or bushing failure;” “inspection required before use;” “removed for time change (TC)/RC;” “beyond specified tolerance;” and “out of adjustment, which includes out of tolerance/calibration.”

Table 3. DA Form 2410 logged faults for the forward and aft hanger bearings

Logged Fault	Percent of Failures
Bearing or bushing failure	23%
Inspection required before use	12%
Removed for TC/RC	12%
Beyond specified tolerance	11%
Out of adjustment, which includes out of tolerance/calibration	9%
Fails Diagnostic/automatic tests	7%
Worn excessively	4%
Serviceable, no defect	4%
Vibration excessive	3%
Internal failure	2%
Leaking (liquid)	1%
Corroded	1%
Loose	1%
Accident damage	1%
Tension incorrect	1%
Seized	1%
Grooved	1%
Removed for scheduled maintenance	0.5%
Controlled exchange	0.5%
Torque incorrect	0.5%
Binding, which includes friction excessive, locked	0.5%
Improper fit, form, function	0.5%
Aviation Safety Action Message/ Technical Bulletin compliance	0.3%
Adjustment improper	0.3%
Lubrication (over or under) or absent	0.3%

Table 3. DA Form 2410 logged faults for the forward and aft hanger bearings (continued)

Logged Fault	Percent of Failures
Elongated	0.3%
Calibration incorrect	0.3%
Resistance low	0.3%
Removed for Safety of Flight message or use analysis	0.2%
Component removed/reinstalled to facilitate other maintenance	0.2%
Brush failure/worn excessively	0.2%
Scored	0.2%
Chafed	0.2%
Faulty reading	0.2%
Bent	0.2%
Buckled or twisted	0.2%
Grand Total	100%

2.4 RELIABILITY IMPROVEMENT THROUGH FAILURE IDENTIFICATION AND REPORTING COMPONENT HISTORY

The U.S. Army also tracks component faults found while a part is being inducted and processed in overhaul at the Corpus Christi Army Depot (CCAD) in Corpus Christi, Texas. The Reliability Improvement through Failure Identification and Reporting (RIMFIRE) program is a U.S. Army contracted program that places inspectors in the CCAD production line. For specific components of interest, RIMFIRE inspectors are chartered to find and document all hardware faults discovered during the pre-shop analysis teardown prior to component induction into the overhaul line. These faults are documented for AED engineers to review and, similar to the DA Form 2410 database, allows engineers to focus on developing solutions to decrease maintenance burdens for premature removals. The RIMFIRE results are categorized by fault mode and compiled into statistical results. However, unlike the DA Form 2410 database, the RIMFIRE data are reviewed and cleansed on an annual basis by engineers and technicians to ensure the data are as accurate as possible.

RIMFIRE is also used by CBM to identify false negatives to capture faulted parts not discovered by legacy maintenance or CBM sensor alerts. Identification of false negatives on critical components reveals potential safety issues to AED engineers and the aircraft platform managers. Similarly, RIMFIRE identifies false positives for the CBM programs. Drive system components, such as gearboxes that trigger an excessive vibration or a bearing energy (BE) alert, are not authorized to be disassembled in the field. When this occurs, these types of drive system components are sent to CCAD for overhaul. Authorization for these component removals with HUMS alerts is accomplished at the discretion of the PMO working groups at Redstone Arsenal. If the CCAD overhaul pre-shop analysis finds no hardware faults present in the suspect drivetrain components, the HUMS alert is documented as a false alert and cause of unnecessary maintenance.

RIMFIRE was contracted to begin evaluating the MRSP and TRDS hanger bearings for this U.S. Army helicopter in March of 2011. Because of the recent initiation of these component evaluations, there is little RIMFIRE data to utilize for analysis in this study. However, RIMFIRE is discussed in this paper to illustrate part of the U.S. Army's data gathering methods to facilitate the RCM process prior to deciding on a solution path for recurring component faults.

2.5 DESIRED MONITORING & ADS 79 CBM APPLICABILITY/BENEFITS

The U.S. Army has two desired CBM end states for HUMS applications [4]: maintenance enhancement and maintenance modification/replacement. The selection of an end state or a combination of end states by a PMO is dependent on the component characteristics of the particular part, including O&S costs. These end states are pursued to reduce maintenance burden caused by repetitive maintenance or a fault's secondary damage; increase safety through the addition of sensors; increase aircraft availability; and/or reduce O&S costs.

Because of the time and cost burden of maintaining aircraft drive system and dynamic components, U.S. Army Aviation PMOs increasingly seek reductions in maintenance and increases in time on wing for these legacy systems. This is understandable because these flight critical systems have perpetually been expensive to maintain (see table 4) and tend to draw focus for improvements even in low flight time demand rates during peacetime.

Table 4. Percent parts cost per flight hour for parts listed

Main Transmission	41.0%
TRGB Assembly	11.0%
Right Hand Side Nose Gearbox Assembly	7.0%
Left Hand Side Nose Gearbox Assembly	5.7%
IGB Assembly	3.6%
MRSP Assembly	6.5%
Tail Rotor Swashplate Assembly	8.1%
Auxiliary Power Unit Clutch	6.8%
Spur Gear Shaft	6.7%
MRSP Bearing	0.2%
Tail Rotor Swashplate Bearing	0.1%
Hanger Bearing Aft	2.1%
Hanger Bearing Forward	1.2%
Total Percent for Parts Listed	100%

If maintenance enhancement is the desired HUMS application to achieve CBM benefits, then the maintenance enhancement results in optional/elective maintenance that is usually selected to trend components over time while retaining the legacy maintenance practices to ensure safety. There are numerous publications addressing the enhancement of legacy maintenance practices using vibratory CBM and related algorithms and sensors [8 and 9]. From an airworthiness risk perspective, implementing vibratory CBM as a maintenance enhancement does not require the same testing rigor and robust design as implementing CBM as a maintenance modification or replacement. The enhancement method also allows for time to mature condition indicators (CIs) and health indicators (HIs) on wing using fielded aircraft as research platforms while conducting normal missions and enables advance warning of component degradation.

If legacy maintenance modification/replacement is the desired HUMS application to achieve CBM benefits, then the requests for aviation maintenance credits are sent from the PMOs to AED for testing requirements and specimen quantity estimates to: (1) extend TBOs via additional endurance testing/experience and teardown analysis (TDA), (2) extend TBOs using vibratory CBM, or (3) transition from TBO maintenance to On Condition maintenance. In the case of the latter two scenarios, qualified vibration-based, on-board monitoring systems with verification and validation (V&V) algorithms are used on legacy systems to modify or replace maintenance. The algorithms output hardware CIs and HIs to characterize the health of both faulted and unfaulted dynamic mechanical components in the rotorcraft propulsion systems.

Pursuing the three types of requests for maintenance credits involves an understanding and evaluation of costs, schedule, and technical constraints. For example, TBO extension requests are constrained by fatigue life limits of the monitored gears, bearings, and shafts to ensure safety. If there are no published fatigue life limits among the monitored gears, bearings, and shafts being reevaluated, then the system may also be considered for On Condition pending the results of CI/HI testing and analysis. Other factors impacting the evaluation may involve consideration of mandatory component replacement or "no build windows" whenever drivetrain/dynamic components are sent to the maintenance depot. "No build window" refers to a depot process of not rebuilding a gearbox or dynamic component incorporating a fatigue life limited component that is within a specified proximity range of the published retirement life.

Another constraint AED considers if vibratory CBM is desired by the PMO to facilitate TBO extensions (as in the case for the MRSP and TRDS hanger bearings) is that vibration-based monitoring is currently limited to trending degradation and diagnosing degraded states at an observed moment [10]. CBM alerts are then provided specifying a time horizon for preventive maintenance action to preclude impending system failure. This is in contrast to prognostics for predicting remaining life. As a result, extending TBO intervals using vibration monitoring is limited to that of measuring vibration characteristics from tolerable damage, wear, and tear conditions (tolerable defined as the ability to operate with defects for two vibration data download intervals). These characteristics are correlated to physical evaluations from TDA direct evidence by the U.S. Army after CBM alerts occur.

If a transition from a TBO to On Condition approach is undertaken, verifying and validating the algorithms will typically require supporting data of faulted and unfaulted components from both the field and test stands. At present, this approach is usually constrained by the lengthy time and high costs required for hardware/software V&V, as well as acquisition of faulted hardware. To validate the vibratory HUMS's abilities to accurately detect faulted and unfaulted parts for TBO extension or On Condition, HUMS CIs/HIs being evaluated should be able to correctly categorize both faulted and unfaulted components using a statistically significant sample size [11] for each failure mode. Supporting rationale for statistically significant substantiation is found in reference 12. In statistical analysis, the U.S. Army uses 90% detection reliability based on historical usage of these figures for risk assessments. To confirm the faults, the U.S. Army requires the HUMS faulted component to be disassembled and inspected by engineers to verify, using direct evidence [4 and 13], that a fault actually occurred. The HUMS must also correctly classify the fault; the system would detect a bearing fault and, on disassembly, the fault would be detected on the correct bearing.

Within the aforementioned validations constraints, additional technical difficulties to respond to the PMO requests for CBM maintenance credits include:

- Insufficient and statistically insignificant data for V&V
- The maturity of vibratory algorithms and sensors for monitoring drive systems and dynamic components may not be adequate to independently maintain acceptable risk levels
- There is no generic or proven V&V framework available [14]
- V&V of each CBM subsystem requires different techniques and specifications [14]
- The existence of health management issues and challenges specific to rotorcraft dynamic mechanical components in the main power train [15]
- The application of non-destructive inspection confidence and reliability criteria [16] to vibratory CBM devices/algorithms has, so far, proven to be elusive (i.e., 90% probability of detection with 90–95% confidence) for dynamic mechanical systems
- The process for ensuring quality integrity of ground-based station (GBS) software may vary depending on the criticality of time-based maintenance calculations performed

Given the constraints and associated implications, how to use a solution to extend time on wing via TBO extensions from follow on endurance testing/experience, transition to On Condition via verified/validated CBM monitoring system, or a hybrid of the two options is best addressed in an RCM investigation [5].

The RCM analysis for both the MRSP and TRDS hanger bearings resulted in a desire by the helicopter PMO to extend the hanger bearing TBO from 2750 flight hours and the MRSP bearing retirement life from 2250 flight hours. Extensions by the PMO were added in increments of 250 hours to match current phased maintenance schedules.

The MRSP bearing is normally believed to have a finite life based on speeds, loads, lubricant, and operating temperatures, which qualification should have established. Although nothing has changed relative to these variables, the retirement life nomenclature is an artifact from a previous design reliant on grease lifing. However, analysis indicates the MRSP bearing is capable of 15,372 flight hours if grease life was not a factor. To substantiate a MRSP bearing life extension, discussions with ExxonMobil and additional MRSP bearing testing for CI/HI verification and validation prior to fielding on U.S. Army rotorcraft is required.

To quantify and qualify the benefits (credits) of maintenance modification/replacement through HUMS, the U.S. Army examines:

- The number of aircraft in a fleet involved.
- The maintenance man hours required to change out the components under evaluation.
- The intangible benefits achieved with increased aircraft availability during wartime.
- The benefits achieved with an estimated parts inventory reduction.
- The cost benefit ratio of component test and analysis evaluation to achieve the maintenance credit.
- The time and cost to develop, provision, field, and maintain the HUMS configuration changes on fleet aircraft and GBSs.

For the MRSP and TRDS hanger bearings time on wing extension evaluations, the U.S. Army uses two methods of collection faults to validate the effectiveness of CI: field faults and seeded faults. Fielded faults are collected through the Quality Deficiency Report (QDR) process. Field faults occur on the aircraft naturally in fleet aircraft and are monitored by HUMS, allowing data to be obtained on faults from field-induced usage and environments. To augment their accrual of fielded faults, the U.S. Army conducts seeded fault testing. Note, however, the seeded fault testing typically lacks, to varying degrees, the actual environmental impacts.

The desired tangible and intangible benefits of the vibratory HUMS (known as the MSPU) on this U.S. Army helicopter MRSP and the TRDS hanger bearings include the following:

- TBO extensions to decrease the number of demands for parts from both the field and required spares in inventory.
- Increase the notification time to the maintainer of an impending failure, thereby increasing the time to order spare parts and schedule maintenance.
- Increase aircraft wartime availability due to reduction in unscheduled maintenance events.
- Decreased secondary damage from broken hardware because of advance notification of primary faults from HUMS.
- Decreased unscheduled maintenance (increasing readiness) and associated man hours (see table 5).
- The proposed CBM methods using the MSPU HUMS will help fleet management and logistics by providing advance notification pertaining to supply chain needs when tying the GBS alerts to the inventory requirements database. This process is currently under U.S. Army consideration to facilitate reductions in extreme component demand variations and forecast accurate running inventories.

Table 5. MRSP and TRDS hanger bearing remove/replace maintenance man hours

Component	Related Components	Maintenance Man-hours to Remove	Maintenance Man-hours to Replace	Overhaul Man-hours
MRSP Bearing				
	Rotor Blades	4.3	4.3	
	Rotor Head	6.7	6.7	
	Swashplate	2.3	2.3	
	Swashplate Bearing Remove & Replace			2.6
TRDS Hanger Bearing				
	Forward Bearing Assembly	0.9	0.9	6
	Aft Bearing Assembly	0.8	0.8	2.1

2.6 MSPU COMPONENT DESIGN, OPERATION, AND MAINTENANCE

The MSPU is a Data Source Collector (DSC; see figure 12) formally made by Intelligence Automation Corporation (IAC) and recently acquired by Honeywell International. This is the U.S. Army selected HUMS for monitoring, among many parameters, the MRSP and TRDS hanger bearing vibrations for this U.S. Army helicopter. The MSPU collects accelerometer sensor data (see figure 13) and aircraft state data, processes CIs/HIs, stores data, and provides data transfer capability to a GBS. Using the GBS, the data are then monitored by the maintainer and sent to AED engineers over a global enterprise for storage and analysis. Through analysis and algorithm modifications, the CIs/HIs are periodically updated to improve sensitivities and alert thresholds after both faulted and unfaulted HUMS component conditions are confirmed by direct evidence via TDAs.

(a) (b)

Figure 12. The (a) MSPU DSC and (b) control head

Figure 13. MSPU accelerometers

The MSPU utilizes up to 36 accelerometers located around the aircraft to measure vibration information; it then sends the vibration information to the DSC (the U.S. Army helicopter model discussed in this report uses 18 of the 36 accelerometer channels). The DSC then converts most of the vibratory signals into CIs and HIs via algorithms. The raw signals not converted in the DSC are retained for conversion in the GBS.

Data are downloaded from the aircraft via a Portable Maintenance Aid or Unit Level Logistics System Aviation Enhanced laptop computer and then uploaded to the GBS. At the GBS, the maintainer is able to update logbook information, capture component alerts, trend changes in sensor signals, and decide what type of maintenance is needed. This information may also be sent to the unit commander to determine aircraft availability and facilitate mission planning. The information is then sent to a battalion level server, which retains a copy, followed by transmission to the enterprise network. The enterprise is a set of servers that distributes the information via satellite communication to the maintainers who use the information for analytical and logistical purposes.

2.6.1 System Installation & Validation

The MSPU HUMS is a U.S. Army qualified installation (analogous to a Supplemental Type Certificated installation) on the U.S. Army helicopter discussed in this report. It is installed by field representatives from Honeywell in accordance with an airworthiness release (AWR). The AWR outlines the limitations, restrictions, and operation of the MSPU; configuration and installation details; and inspection, maintenance, and electronic logbook instructions.

The AWR also authorizes relief from mandatory inspections as well as TBO and retirement life extensions (maintenance credits) that differ from those listed in the aircraft technical manuals, such as relief from the MRSP 50-hour hand rotation inspection if a HUMS is installed and operational.

Once the MSPU HUMS is installed in the aircraft, MSPU data are monitored by the maintainers but also by a working group that looks for outliers and anomalies in the data provided through the enterprise network. The working group meets at Redstone Arsenal and is comprised of AED drivetrain/vibration/systems engineers and PMO representatives. Discussions within the working group primarily address:

- Component removal and QDR decisions based on HUMS alerts occurring prior to legacy maintenance schedules.
- Recent TDAs on QDR components from the field; status findings and update statistics on true alerts; and false alerts for monitored components.
- The path forward for monitoring specific aircraft components via RCM conclusions/RIMFIRE results.
- Desired MSPU software and technical manual changes for both the MSPU and GBS.
- Any recent seeded fault test stand data results.
- AWR status relative to test findings and field data.

QDR hardware for monitored components is delivered to either the Redstone Test Center (RTC) or the Analytical Investigation Branch of CCAD. The RTC and CCAD TDA reports from QDR drive train bearings, shafts, gears, and dynamic component bearings are evaluated by the AED Propulsion Division engineers. For the U.S. Army helicopter discussed in this report, this includes the MRSP and TRDS hanger bearings. The AED Propulsion Division engineers evaluate the physical condition of these components based on their knowledge of the systems and experience from past teardowns and assign a color code from an established scorecard (see table 6); the color codes correspond to maintenance actions and time horizons for maintenance to avoid failures and secondary damage. In addition, legacy maintenance is ensuring continued airworthiness, usually through chip detectors, temperature sensors, lubricant inspections, and other periodic vibration checks.

Table 6. TDA scorecard

Score Card				
Color Code	Operational Capability	Maintenance Action Required	Time Horizon for Maintenance	Impact to Components
	Fully Functional	No Maintenance Required	Form 2410 Remaining Life	No Perceptible Impact to Components Mating Parts
	Functional with Degraded Performance	Monitor Frequently	> 100 Hrs	Eventual Component/Mating Part Degradation from Light Metal Contamination, Wear, and Vibration Translation
	Reduced Functionality	Maintain as Soon as Practical	10 Hrs < X < 100 Hrs	Moderate Metal Contamination Resulting in Accelerated Component/Mating Part Degradation
	Critical or Mission Aborting Failure Mode: Lack of Functionality Results in a RED X*	Maintain Immediately	None	Heavy Metal Contamination Resulting in Catastrophic Potential

* as defined in DA PAM 738-751

The AED Propulsion Division assigns the hardware condition color code, and supporting information is then sent to the AED Aeromechanics Division. AED Aeromechanics evaluates the vibratory CI to determine if the MSPU software alert, displayed on the GBS, appropriately matched the component physical condition assigned by the AED Propulsion Division. If not, then AED Aeromechanics may modify the algorithm threshold alert level in a laboratory environment to reflect the actual component condition depending on the number of false alerts in the collected fleet data. The modified alert level is then run against the collected data from the specific helicopter fleet for the component to determine if the threshold still captures previously confirmed faulted hardware and does not create an increase in false alerts for other aircraft. After a number of threshold modifications are confirmed as beneficial, the laboratory software is validated either on board a test aircraft or, in the future, at the Aviation Systems Integration Facility (ASIF). Following validation, AED Aeromechanics provides a recommendation to the working group to upgrade the fielded aircraft and GBS software. The working group then coordinates fleet implementation of the software.

The MSPU HUMS CIs/HIs for a component intended for legacy maintenance modification/replacement continue to be adjusted to a point where statistical significance in the number of samples is obtained for validation using 90% detection reliability with 90% confidence for all the CIs/HIs and all failure modes on that component. This is necessary to substantiate safety issue avoidance of false negatives on critical parts (i.e., faulted critical parts not detected by the HUMS). Subsequently, the MSPU with validated CIs/HIs may be used as the sole system for TBO and On Condition maintenance determination in lieu of flight hours.

The obvious hurdle in achieving this validation goal when modifying/replacing legacy maintenance is obtaining enough faulted and non-faulted samples with TDA direct evidence and monitoring data on relatively robust designs that do not fail on a frequent basis. To reduce the magnitude of this hurdle, the U.S. Army is proposing HUMS implementation on OEM Production and Depot Overhaul acceptance test stands to collect monitored data on non-faulted components. In addition, AED is determining an acceptable quantity of flight hours on a fielded component, with consistent HUMS readings in the healthy range, that do not require a TDA so that these data could be used as a non-faulted component sample data point. For faulted components, the current alternatives only consist of monitored field components and seeded fault components which have undergone TDA.

Though the majority of MSPU alerts on U.S. Army helicopters are not mature and are typically used as maintenance enhancements, the incorporation of sensors and processors on fielded aircraft allows for a laboratory/research environment to exist on fleet aircraft performing their missions to facilitate maturation of HUMS thresholds used as maintenance alerts.

2.6.2 Credit Validation Process Plan

The PMO for the helicopter addressed in this report has not documented an official plan pertaining to the validation of maintenance credits for the MRSP and TRDS hanger bearings. However, the following describes what a planned maintenance credit and the validation process for extending component time on wing would resemble. This example checklist incorporates details discussed in the previous sections of this report plus additional lessons learned using a U.S. Army helicopter MRSP bearing as an example.

Example HUMS credit validation planning checklist for vibratory HUMS to achieve CBM on legacy rotorcraft

Aircraft Model: Specific Aircraft Type and Model Listed

Component Description and Part Number (P/N): MRSP Bearing and Applicable P/N(s) Listed

Intended Goals for Component:

- Short-Term–Enhance legacy MRSP bearing maintenance by adding vibratory HUMS sensor to fleet aircraft and test stands; gathering and storing data; trending vibration data; and maturing fidelity of CI/HI threshold algorithms based on data and TDAs.

- Long-Term–Extend time on wing by modifying legacy retirement life after collecting either sufficient experience base or statistically significant data for all CIs/HIs on faulted and non-faulted MRSP bearings.

Documentation of Processes to Achieve Goals:

Document RCM analysis to identify component constraints and justify cost/benefit ratio for investment costs to attain desired maintenance frequency using reliability analyses and considering impact of failure modes. Include the initial understanding of failure modes that are consequential. Conclude with the most effective course-of-action.

Document preferred integrated elements and architecture to achieve goals. The architecture should consist of hardware and software elements that work together to provide the capabilities inherent in the desired maintenance strategy.

Other areas to document include:

- Required teams, team members, and team responsibilities
- Incremental implementation strategy to test and field time on wing extensions
- Collect sample data for faulted and non-faulted MRSP bearings (field & seeded fault) as shown in appendix B and reference 17
- Document and implement mechanisms to obtain non-faulted samples
- Document and implement mechanisms to obtain faulted samples
- Plan to specify where the sample components should come from and an estimate of how long it will take to obtain the necessary data. Plan to specify how many failed components and the rate at which components and associated data will be obtained (appendix B)
- Schedule to execute plan and achieve incremental cost benefits
- Document plan for continued airworthiness

2.6.3 Plan for Continued Airworthiness Process

During the validation process, the U.S. Army's planned approach for continued airworthiness on the MRSP and TRDS hanger bearings for this helicopter is to rely on legacy maintenance until validation of time on wing extensions are obtained. Legacy maintenance will continue to ensure

baseline flight risk until validation is complete. During the data collection phase for validation, however, the MSPU HUMS will be used to remove components prior to legacy maintenance component removal requirements allowing for data gathering and analysis on bearing fault progressions and false alerts.
Once MSPU HUMS validation is achieved for the MRSP and TRDS hanger bearings, continuous monitoring of false positives and negatives for the tested configurations will continue to ensure that reliability and confidence levels are maintained. This will require the CBM infrastructure established during the research and fielding phase to remain in place. This includes authorizations through AWR and approved technical manuals for the system configuration, installation, operation, maintenance, limitations, and restrictions.

For maintenance credits from validation, the U.S. Army has yet to finalize its standard approach for software validation both on board the aircraft in the MSPU and off board the aircraft in the GBS. Currently, flight test aircraft with new, onboard versions of MSPU software are flown against the older versions of onboard software. A comparison is then made from the older version to the newer version on the same aircraft to ensure no unexpected data are encountered. Initially, the older versions of software were compared against the Aviation Vibration Analyzer (AVA) software readings and limits, which ground maintenance used to initiate maintenance in accordance with reference 18. More recently, the ASIF, which incorporates a golden set of data from a test aircraft, exercised the newer versions of MSPU onboard software against a golden set of data from an aircraft with known validated hardware.

With regard to ground stations, GBS software is not part of the seeded fault testing the U.S. Army has been conducting and is, therefore, not discussed in this report.

2.7 VIBRATION MONITORING HISTORY

In 1982, the U.S. Army was experiencing vibration problems with high-speed engine shafts on UH-60 Black Hawks. In turn, they began using a Chadwick Vibrex system to detect high vibrations and instituted a 100-hour vibration check on the high-speed engine shafts. The Vibrex was an analog system requiring the user to dial in the frequency of interest. Once the frequency was selected, the Vibrex would indicate the amplitude of the frequency measured from the aircraft. This was the first helicopter application developed by the U.S. Army involving vibration monitoring techniques.

Later, the U.S. Army conducted a non-developmental competition resulting in a 1991 contract award to implement the AVA tools to facilitate U.S. Army maintenance for helicopter, rotor track, and balance. The vibration measuring equipment at the time was too expensive to have installed on all aircraft. In addition, the function of the equipment was not needed for every flight. As a result, the U.S. Army procured one AVA for every 10 aircraft to be used as maintenance support equipment.

On the helicopter model addressed in this report, the AVA was used exclusively as a vibration analysis tool for the TRGB and IGB. However, the original AVA signals were less reliable on this helicopter than anticipated and resulted in thousands of false alarms. Eventually the vibration measuring equipment and electronics became smaller, more reliable, and less expensive. In 1998, the AED Aeromechanics Division teamed with the South Carolina National Guard (SCNG) and

IAC to develop a light industrial grade, inexpensive, onboard Vibration Management Enhancement Program (VMEP) for vibration signature analysis. Once installed and used for maintenance, the SCNG demonstrated there was a significant decrease in O&S costs due in part to rotor track and balance maintenance.

With development and analytical software tools like C++ and VxWorks, the U.S. Army found it easier to compile and dissect information and obtain expedient, more meaningful changes to threshold alerts. As hardware and software were updated, the VMEP evolved into the MSPU, which is capable of recording aircraft state data along with the previously established accelerometer signals. Tables 7 and 8 list the CIs developed and currently fielded for the MRSP and TRDS hanger bearings:

Table 7. MSPU MRSP bearing CI

CI Name	Yellow//Red Limits (g)	Frequencies (HZ)	Notes
MRSP BE	7//14 g	100–5,900	Corrosion, Broken Cage
MRSP Shock Pulse Energy	3//6 g	12,500–17,500	Corrosion, Broken Cage
MRSP Amplitude Demodulated	5//10 g	50–550	

Table 8. TRDS Forward and aft hanger bearing CI

CI Name	Yellow//Red Limits (IPS or g)	Frequencies (HZ)	Notes
Hanger Bearing 1 per Revolution Vibe	2//3 IPS	Max peak within 60–100	Shaft imbalance
Hanger Bearing 2 per Revolution Vibe	2//3IPS	Max peak within 152–172	Shaft imbalance and Misalignment
Hanger Bearing Energy	7//14 g	100–1,100	Corrosion, pitting/spalling
Hanger Bearing Shock Pulse Energy	15//30 g	12,500–17,500	Corrosion, pitting
Hanger Bearing AMD Bearing Vibe	50//100 g	Max peak within 170–970	

AMD = amplitude demodulated

To date, the history of monitoring the MRSP bearings for the helicopter addressed in this report has provided 14 TDAs for suspected spalled bearings from monitored field aircraft from 2007–2011. Three of the TDAs were rated as Red, indicating they required mandatory maintenance (see table 6). Seven TDAs were rated as Yellow, with operation within specified limits but elevated vibration and optional maintenance able to be scheduled to avoid progressing to the Red condition. Four TDAs were rated Green for continued operation without elevated or increased vibration. The four Green readings may be used to verify the algorithms' abilities to correctly monitor unfaulted conditions with confirmation of hardware condition. The Yellow readings may be used to adjust the CI/HI thresholds and trend increases in degrading components. The Red readings are used to validate the CI/HI and sought after maintenance credits. The Red readings are the most important of the three condition codes because Red is the reading developed for mandating a part be removed immediately for maintenance, whereas all other conditions were developed for optional maintenance.

With regard to the TRDS hanger bearing addressed in this report, fleet monitoring history from 2009–2011 provided eight TDAs from monitored aircraft. These TDAs resulted in seven Green-rated components (false positive alerts) for suspected spalled bearings by the MSPU. In addition, one Yellow-rated component from the field was confirmed in a TDA.

Though the collection of additional field MRSP and TRDS hanger bearings flagged for faults continue to be received and analyzed to mature CIs and fulfill sample size requirements to extend time on wing, the U.S. Army elected to expedite data collection using seeded fault test stands. Sections 3–6 address U.S. Army MRSP and TRDS hanger bearing seeded fault test activities.

3. PRE-TEST ACTIVITIES

Prior to collecting seeded fault data points, AED conducts CBM Test Readiness Reviews (TRRs). A CBM Test Requirements Checklist for the TRRs is provided in reference 19 to assist in understanding the requisite elements and activities to be reviewed before seeded fault testing is initiated. In addition, status updates are obtained from other U.S. Army test facilities supporting seeded fault investigations of components of common interest. These status updates with other facilities, having recent findings, may cause last minute changes in testing initiated by AED. This section encompasses the various aspects of MRSP and TRDS hanger bearing test facilities, test stands, data acquisition, test article configurations, seeded fault applications, and test procedures deemed necessary to initiate seeded fault testing.

3.1 TEST FACILITIES (AVIATION FLIGHT TEST DIRECTORATE/ARMY RESEARCH LABORATORY/USC)

AED uses several different test facilities to gather the data in support of validation for extending component time on wing. For the TRDS hanger bearings, the Army Research Laboratory (ARL) was consulted for the availability of seeded fault specimens and their latest seeded fault CI findings. Additionally, USC and the Aviation Flight Test Directorate (AFTD; formerly the Army Aviation Technical Test Center) were contracted to perform testing on seeded fault specimens. For the MRSP bearing, USC and AFTD were the supporting test facilities used by AED to conduct seeded fault testing. All TDAs for sample data point validation were conducted at RTC.

3.1.1 AFTD Test Aircraft and Instrumentation

An AFTD test aircraft was authorized to conduct on-wing ground testing of MRSP and TRSP hanger bearings seeded with faults in accordance with [20] test points using a VMEP MSPU

HUMS instrumented aircraft [21]. Accelerometers were incorporated around the bearing components in the same manner as on field aircraft. Thermocouples were also installed near the hanger bearings. Readings were obtained by the HUMS to provide CI calibration, improve CI algorithms, and adjust current alert thresholds (tables 7 and 8). Table 9 provides the listing of components and their respective conditions tested during two ground run cycles lasting 75 minutes each.

Table 9: Tail rotor drive train test stand hardware used in AFTD on-wing testing

Serial Number	Component	Condition at Start of Test
0888	MRSP Assembly	No Fault
2581	Fwd Hanger Bearing	Failed Field Nutation Check but Quality Deficiency Evaluation Found No Fault
2043	Fwd Hanger Bearing	Leaking Grease
1605	Aft Hanger Bearing	No Fault
AED-003	Aft Hanger Bearing	Leaking Grease

Additional aircraft testing is conducted using fielded aircraft as research platforms while the aircraft are conducting normal missions, similar to flight data recorders used for Flight Operations Quality Assurance programs. This enables AED to gather real world data at no cost because data are downloaded from the aircraft by field maintainers at regular intervals. Future seeded fault testing on test aircraft during ground runs is also being planned to supplement test stand validation.

3.1.2 ARL and USC Test Stands and Instrumentation

Sections 3.1.2.1–3.1.2.3 outline the equipment and general test stand configurations of the ARL and USC test stands. This provides an understanding of the requirements to develop a simulated representation of the aircraft component vibration and obtain CI readings for the MRSP and TRDS hanger bearings on test stands.

3.1.2.1 ARL TRDS Hanger Bearing Test Stands and Instrumentation

Consultation with ARL provided the TRDS hanger bearing test stand information [22]. Use of the data from the two ARL test stands for validating an extension of the TRDS hanger bearing TBO was combined with the results from USC's Tail Rotor Drive Train (TRDT) test stand and is further discussed in section 6. Instrumentation for the first ARL test stand (see figure 14) relied on the VMEP MSPU, as detailed in reference 22. In addition, a high-frequency accelerometer was incorporated in this first test stand to permit high-frequency raw data collection for further analysis and manipulation. The first test stand consisted of a forward hanger bearing assembly from the aircraft; variable speed electric motor; belt and pulley system; and shafting system attached to a heavy machine base resting on a large bedplate. The shafting was aligned using a laser alignment system and balanced. Bearing radial loads were 12 pounds, which is lighter than encountered on the aircraft. The CI software used in the field was used on the test stand.

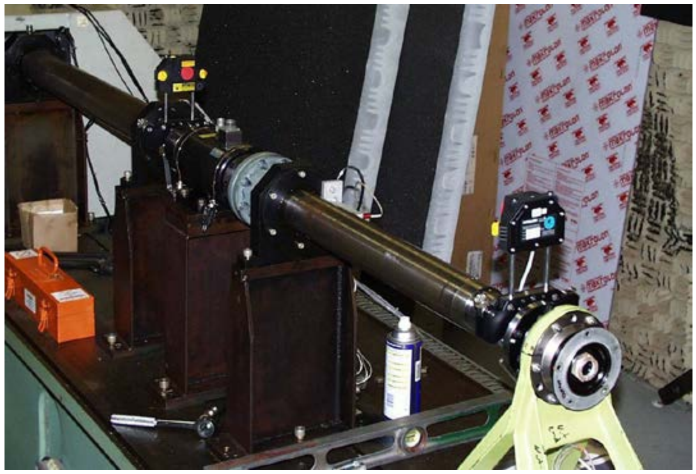


Figure 14. ARL TRDS forward hanger bearing test stand

One purpose of the first ARL test stand was to obtain indications of whether CIs programmed on the aircraft would respond to fault modes simulated by seeded faults. Another purpose was to allow for further analysis of raw acceleration data using different signal processing methods. The three seeded fault mechanisms were simulated spall line on the inner race, corrosion damage from salt water, and damage from sand contamination. All three fault mechanisms were expected to lead to the spalling failure mode.

The second ARL hanger bearing test stand (see figure 15) consisted of the bearing rig depicted in reference 22, which allowed for up to eight bearings to be run at aircraft operating speeds on a single shaft and in a heated environment to simulate degraded grease up to 315°F. Bearings corrosion damaged with saltwater and bearings damaged with small drilled indents were also run on this stand. Thermocouples, accelerometers, and field CI software were also used in the test stand. The degraded grease fault was a mechanism expected to result in either a spalling or seizure (thermal runaway) failure mode.

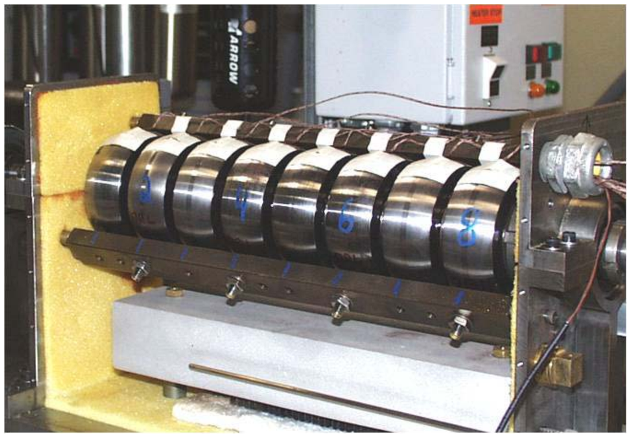


Figure 15. ARL hanger bearing degraded grease test stand

3.1.2.2 USC TRDT Test Stand and Instrumentation

The USC TRDT test stand (figures 16–18) was designed so that seeded fault testing could be performed on multiple TRDT components. All TRDSs, forward/aft hanger bearing assemblies, damper assemblies, anti-flail brackets, IGB, TRGB, and TRSP hardware components consist of actual aircraft hardware. Testing on individual components was conducted in a serial manner so as not to jeopardize altering vibration signals of interest from one component to another, as could be the case if two components were tested in parallel. The TRDT test stand hardware components, though not considered test articles under this test plan, were instrumented with standard MSPU sensors and provided additional CI signature comparisons between the field aircraft and the test stand.

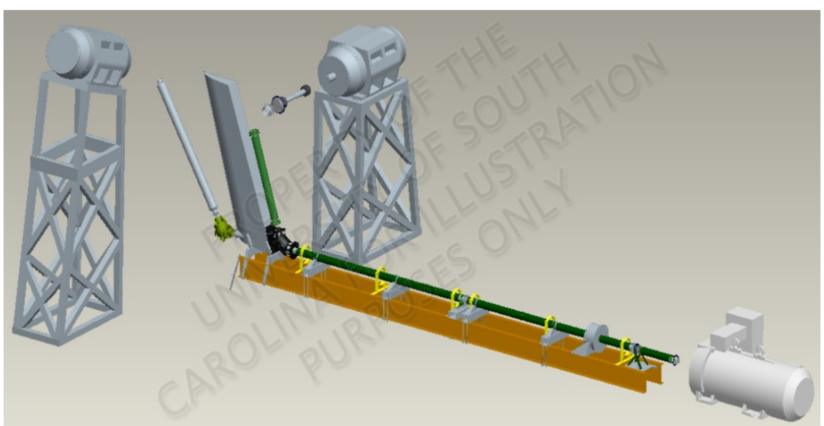


Figure 16. TRDT test stand configuration

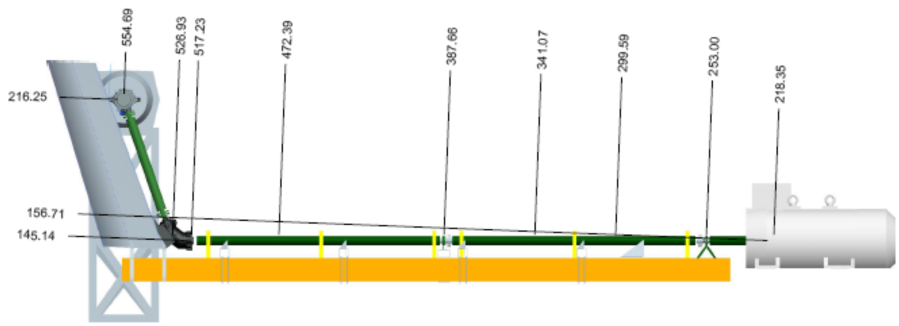


Figure 17. TRDS test stand profile

Figure 18. Actual USC TRDT test stand

The TRDT fixture incorporated an electric drive motor to drive the USC TRDT and a rigid test fixture constructed with components of the U.S. Army helicopter discussed in this report. The installed TRDSs were misaligned 1.3 degrees, as shown in figure 19, because the aircraft specification, DRC-S-H10000B, states “Misalignment: Each flexible coupling shall be capable of operating at 1.3 degrees of angular misalignment at continuous operating torque and speed…” The installed TRDSs also included the maximum allowed imbalance of 1 IPS (Depot Maintenance Work Requirement 1-1615-336 [23]). Once installed on the test stand, each drive shaft assembly was imbalanced an additional amount equivalent to the on-wing average imbalance, as recorded by fielded MSPU equipment. This value creates a 1 per revolution reading on the forward and aft hanger bearings.

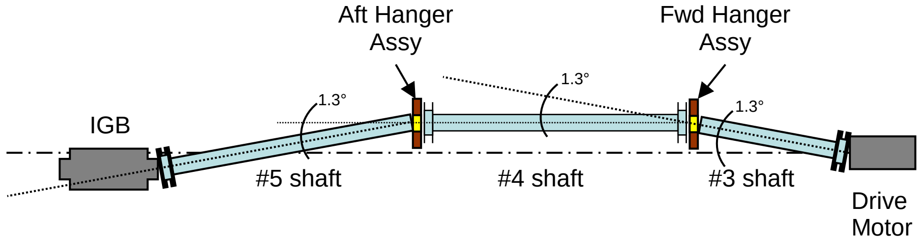
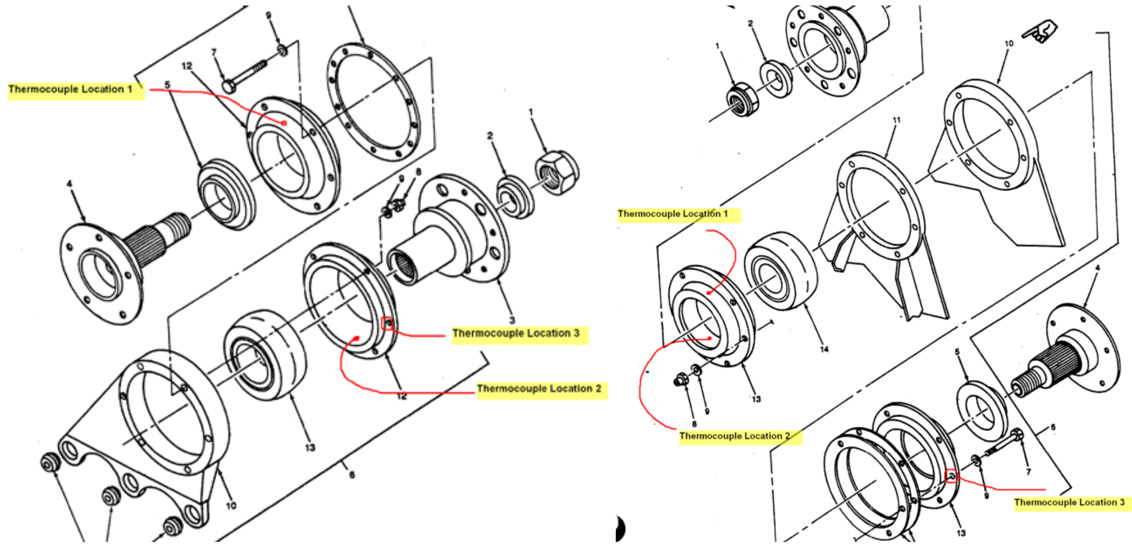


Figure 19. TRDT test stand drive shaft misalignment requirement (top-down view)

Shaft speed is a primary parameter for the TRDS hanger bearing test instrumentation. A tachometer signal of the TRDT motor speed was provided to the MSPU/VMEP to track the bearings' turn speed. TRDS hanger bearings could be tested without a torque load. However, the full test stand was run with a torque load of 1222 lb ft (as measured at the TRGB output shaft) to provide realistic FPG101 torque load to all tail drive train components (gearboxes, swash plates, etc.). The TRDSs (#3, #4, and #5 in figure 19) were run at a steady state of 40,863 RPM to represent the 101% speed of the aircraft system.

The test stand was instrumented with the following data acquisition systems (DAQs) and sensing collected for all the tests:

- Loading and Torque: Digital telemetry load cells
- Rotational Speed in RPM: Optical tag, track, & locate measuring device and motor encoders
- Vibration: MSPU equipment captures data when the tests are run to include the:
    - IAC-1209 MSPU configured with hanger bearing diagnostics identical to software setup version 48
    - Hanger bearing accelerometers installed on the test stand in the exact aircraft configuration [24]
- Temperature: Thermocouples or other temperature measuring devices are attached to the outside of the Teflon-lined bearing housing of the forward and aft hanger bearing assemblies (installation shown in figures 20 and 21)
- Acoustic emissions (AE): High-bandwidth accelerometers (AE sensors)



(a) (b)

Figure 20. The (a) aft and (b) forward TRDS hanger bearing thermocouple locations

Figure 21. TRDS forward hanger bearing thermocouple installation

The TRDS hanger bearing seeded faults specifically applied to the USC TRDT test stand consisted of the following seeding mechanisms: hard particle grease contamination to simulate wear, saltwater to simulate corrosion, and loss of grease lubricant to simulate wear. These mechanisms were intended to lead to bearing spall/thermal runaway failure modes.

3.1.2.3 USC MRSP Bearing Test Stand and Instrumentation

The USC MRSP test stand (see figure 22) was designed and built as a universal helicopter MRSP test stand for use in seeded fault testing of multiple U.S. Army aircraft MRSP. The test stand has the data acquisition systems and sensing instrumentation for the MRSP on the helicopter of interest. Unlike the USC TRDT test stand, a torque measurement is required for the MRSP test. The following are the test stand’s data acquisition systems and sensing instrumentation:

- Rotational Speed: Tachometer (TAC-1) signal provided by the tachometer sensor and existing interrupters mounted on the rotating swashplate housing (see figure 6). Drive motor encoders also measure rotational speed and provide a backup source.

- Vibration: MSPU equipment senses and captures all required vibration data (see figures 4 and 5). The IAC-1209 MSPU is configured with MRSP diagnostics identical to software setup version 75. The MRSP accelerometers are installed on the test stand in the exact aircraft configuration [24].

- Temperature: The USC DAQ single Omega TJ36-CASS-18U-6 (or similar) TC-type thermocouple probe is installed through the base of the MRSP assembly stationary swashplate to provide a temperature reading of the bearing inner race. Thermocouple installation is shown in figures 4 and 5. The MRSP fixed housing is modified by RTC to accept the USC DAQ sensor.

- Cyclic Load: Strain gages are installed on each of the four pitch link assemblies. Pitch link loading is measured to provide test stand cyclic loading feedback to ensure the loads are representative of field usage. Installation is shown in figure 11. High-bandwidth accelerometers (AE sensors) were installed by USC to collect additional data, but were not required to meet the objectives of the MRSP test plan.

Figure 22. Actual USC MRSP test stand

3.2 TEST STAND DATA ACQUISITION (ARL/USC)

The test stands at both ARL and USC used the MSPU along with their own DAQ and unique data acquisition software. The DAQs allowed the CI to be monitored and displayed in real time and compared to the data collected and downloaded by the MSPU. The MSPU data for both the test stands and field aircraft were formatted into .var files compatible with AED's vibration software analytical tools.

3.2.1 ARL Data Acquisition for the TRDS Hanger Bearings

Though AED was consulted by ARL for input into the preferred data acquisition scheme, data acquisition for the ARL test stand was accomplished independently from AED and, therefore, is not discussed in detail. ARL used the MSPU to collect their accelerometer signals and process them through the same software algorithms the field aircraft use for CIs. All thermocouples, speed, torque, and broadband root mean square vibration levels at the hanger bearings were recorded at a relatively low data acquisition rate of approximately 100 Hz.

3.2.2 USC Data Acquisition for the TRDS Hanger Bearings

All MSPU data collected during the USC TRDS hanger bearing seeded fault testing was acquired at the end of each day and stored on the USC CBM server. The MSPU was configured to monitor in two modes: monitor and survey. In monitor mode, the MSPU calculates CIs once every two minutes. These data sets were recorded during all operations. Survey mode was initiated manually to collect a five-second raw data sample and archived every hour by the USC test engineer. Special event recording by the MSPU was also manually commanded by the USC test engineer for periods such as high vibratory events.

Because the MSPU cannot display CIs in real time, a USC DAQ was configured to display real time CIs using algorithms similar to those in the MSPU. The USC DAQ was configured to collect five-second data sample blocks in parallel with the MSPU every hour. The USC DAQ automatically records special events in a sliding window two minutes in duration. All parameters (temperatures, vibration, torque, etc.) were saved any time an individual parameter triggered a special event recording window.

3.2.3 USC Data Acquisition for the MRSP Bearing

The MSPU data collected during the USC MRSP bearing seeded fault testing was acquired in a similar manner to the hanger bearings. In MSPU monitor mode, the CIs were calculated once every two minutes. These data sets were collected and calculated regardless of test stand torque. Monitor mode was triggered by the drive shaft tachometer signal when it was between 4.3–5.3 Hz. In survey mode, the MSPU was used to acquire and archive a 3.6-second raw data sample corresponding to 175,000 points at 96 kHz each hour (either manually or automated using a facility control code). Survey mode was operated while the MRSP stand was operating at FPG101 survey state (speed and loading). The MRSP bearing survey mode sampling and calculating windows are each five minutes in duration and are taken each hour. Special event recording by the MSPU was also manually commanded by the test engineer. The data modes were recorded and automatically saved to an external USC hard drive using a USB connection.
The MSPU data were downloaded on the USC external hard drive and the volatile memory flushed after every 250 minutes of MRSP bearing test stand run time. The MRSP bearing test stand was shut down while the MSPU data were flushed. This MSPU flushing exercise also required USC to pause their own DAQ to prevent data gaps between the DAQ and the MSPU. The external hard drive was manually archived at the end of each day to the USC CBM server and the USC secure test data web page. A seeded fault test server may be set up by Honeywell in the future as a secondary repository of MRSP bearing test stand data. The Honeywell test server is AED’s primary repository of MSPU data collected from seeded fault testing.

The USC DAQ system was configured to collect 65,000 points—acquired at 48 kHz every two seconds—for the MRSP bearing test stand. The USC DAQ was also the sole source of temperature data. All USC DAQ data were archived to the USC CBM server. USC could perform independent measurements of vibration and AE. These measurements were not required by the test plan and are optional. These additional data are provided to the government upon request.

3.3 MRSP AND TRDS HANGER BEARING TEST ARTICLES (ARL/AFTD/USC)

To obtain seeded fault test articles for test aircraft and test stands, the U.S. Army uses two different sources for test articles. One is to procure new, unused parts from the OEM or military stock and then seed faults according to the applicable test plan. This method requires a funding source to procure parts. The other method is to obtain old, used parts from the field or depot that either incorporate faults from the field acceptable for testing in accordance with the test plan or are seeded with faults in accordance with the test plan prior to testing. Typically, both acquisition methods are commonly accepted for any U.S. Army seeded fault testing process. This process allows for baseline testing on unfaulted parts followed by testing on faulted field parts to differentiate vibration signals between the two.

A variety of mechanisms are chosen for the MRSP and TRDS hanger bearing designs to induce the two failure modes of spalling and thermal runaway. Some of these mechanisms are capable of leading to both failure modes. For each bearing, the test articles and their intended seeded fault mechanisms are provided in sections 3.3.1–3.3.4.

3.3.1 AFTD MRSP and TRDS Hanger Bearing Test Articles

Two hanger bearings that leaked grease in the field were field faulted components obtained for the AFTD aircraft ground testing. One other hanger bearing was obtained from the field that was turned into the depot for a failed nutation check. The hanger bearing that failed nutation check was reinspected in the RTC laboratory and found to be in good condition without failing repeated nutation checks. The baseline hanger bearings and MRSP bearing used in the AFTD aircraft test were those currently operating on the AFTD test aircraft. These hanger bearings were tested on the aircraft to obtain initial vibration signature data.

No testing on the MRSP bearing was conducted with a faulted bearing, but signal data were obtained from the good MRSP bearing operating on the aircraft.

3.3.2 ARL TRDS Hanger Bearing Test Articles

At least 26 ARL TRDS hanger bearing test articles were purchased for the ARL hanger bearing test stands through a U.S. General Services Administration (GSA) source and were considered to be in new condition as received from the vendor. One hanger bearing used in the field was delivered to ARL from CCAD. Among the ARL hanger bearing test articles, the following seeded faults were implemented (serial numbers [S/Ns] or other unique identifying numbers are in parentheses):

1. 1 bearing was submitted to heat-degraded grease (1328)
2. 2 bearings had reduced grease only (ARL-017, 016)
3. 2 bearings were contaminated with fine sand (ARL-012, 015)
4. 2 bearings were contaminated with course sand (ARL-011, 014)
5. 3 bearings were corroded with salt water (ARL-018, 020, 021)
6. 1 had reduced grease and saltwater corrosion (ARL-019)
7. 3 bearings had machined spalls only (ARL-002, 026, 0358)
8. 4 bearings had machined spalls and submitted to heat-degraded grease (ARL-006, 008, 009, 0010)
9. 1 bearing had heat-degraded grease, reduced grease, and a machined spall (ARL-007)
10. 2 incorporated saltwater corrosion and submitted to heat-degraded grease (1320, 1321)
11. 3 had reduced grease and submitted to heat-degraded grease (ARL-019, 1345, 1311)

Details on seeding the faults in the hanger bearings for the ARL hanger bearing test stand are described in reference 22.

No testing on the MRSP bearing was conducted at ARL, so MRSP bearings were not obtained for the ARL test stand.

3.3.3 USC TRDT Hanger Bearing Test Articles

For the USC test stand, the AED Systems office acquired five new TRDS hanger assemblies (forward and aft) from the GSA inventory to use as baseline hanger bearings. Later, the AED Systems office supplied three hanger bearings from the field, in which USC applied cut seals (AED-001, 002, 003) to allow the bearing grease to leak. The remaining USC hanger bearing test articles were obtained from ARL following completion of their testing. The eight faulted bearings from ARL were provided to USC and included:

- 1 exposed to heat-degraded grease and reduced grease (1311)
- 1 exposed to heat-degraded grease and salt water corrosion (1320)
- 1 contaminated with fine sand (ARL-012)
- 1 machined spall and submitted to heat-degraded grease (ARL-006/SN Test 1)
- 1 reduced grease (ARL-017)
- 1 bearing was received from the depot after being removed from a field aircraft (6163Z1)
- 2 bearings with saltwater corrosion (ARL-021 & ARL-022/020)

Additional hanger bearings were anticipated to be procured to meet test requirements for statistically significant test results. However, hanger bearing seeded fault testing was discontinued based on test results/ramifications and the additional bearings were not procured.

The details on how the faults were seeded are provided in ARL's test documentation in reference 22.

3.3.4 USC MRSP Bearing Test Articles

As of the writing of this report, the MRSP bearing test program had not been completed. Therefore, all of the test articles were not yet obtained. Because of the cost of the MRSPs, AED anticipates obtaining the vast majority of the articles from the field/CCAD. The maximum number of MRSPs obtained for seeded fault testing is anticipated to be 20, as outlined in the test plan and depicted in table 10.

Table 10. MRSP failure modes/faults/specimen numbers

	Fault	Number of Faults	Failure Mode	Total Specimens
A	CORROSION (Natural Fault)	1	THERMAL	10
B	CORROSION (Saltwater Injection)	1		
C	CORROSION (Acid-Etching)	1		
D	LOSS OF GREASE (Film)	3		
E	CONTAMINATED GREASE (Fine Sand)	2		
F	CONTAMINATED GREASE (Coarse Sand)	2		
A	CORROSION (Natural Fault)	1	SPALLING	10
B	CORROSION (Saltwater Injection)	1		
C	CORROSION (Acid-Etching)	1		
D	LOSS OF GREASE (Film)	3		
E	CONTAMINATED GREASE (Fine Sand)	1		
F	CONTAMINATED GREASE (Coarse Sand)	2		
G	CORROSION (Heat-Quenching)	1		

MRSP test articles are selected from one of two categories:

- Category 1: Field MRSPs returned from the field, having completed a TDA to confirm current condition, reassembled with no part changes, and incorporating pre-existing conditions tested to correlate on-aircraft signals to the USC MRSP test stand vibration data with reassembled MRSPs

- Category 2: Field MRSPs returned from the field, not modified or overhauled, and receiving a specified seeded fault from table 10

To date, the following MRSP bearing seeded faults have been applied and tested:

- 1 bearing with 540 coarse sand (0888)
- 1 bearing with thin film grease (0363)
- 1 bearing with thin film grease (0390)
- 1 bearing field induced static corrosion (0241)

Additional MRSP bearings were recently received and are planned to be seeded for faults in accordance with reference 17. Details on seeding the faults in the MRSP bearings for the USC MRSP bearing test stand are also described in reference 17.

3.4 TEST PROCEDURE

Testing must be outlined to make it clear to the test facility and testing engineers how to proceed through the test process. This includes developing procedures for test article and test stand configuration definition/inspection; check out runs; instrumentation calibration checks; sample data transmittal/analysis/storage; baseline testing; test stand maintenance; periodic data status review; and test amendment/termination events.

3.4.1 Test Article Inspection and Installation

Whenever a part is brought in for testing from the depot, field aircraft, or vendors, the component must be verified for the condition required for testing. Upon delivery of components to the test facility, a receiving inspection is performed to ensure the new or faulted component condition is capable of operating during the test while providing the best opportunity to develop expected test data. Any known or suspected damage that may have been caused in transit is brought to the attention of the AED Seeded Fault Test Integrated Product Team (IPT) prior to installation of the assembly into the test stand. These inspections consist of examination for torn seals, leaking fluids, visible external cracks, and confirmation of S/N. The results of these inspections are documented using photographs and descriptions that are provided to the AED for review and reporting. Once the receiving inspection has been completed, the assemblies are mounted on the test stands and serviced per normal aircraft maintenance requirements.

3.4.2 Operational Checks

Following normal service checks for the test stands and components under test, operational checks are conducted, followed by an initial run-up for stand check out. Initial run-ups of each unit under test (UUT) follow a build-up approach by slow running the assembly up to normal operating speed with previously established signal stabilization times. If any unexpected vibrations, resonance, or noises are noted during the initial run-up, the operational check is discontinued immediately and AED Seeded Fault Test IPT notified for resolution development.

3.4.3 Baseline Signature of Test Articles

After the successful shakedown of the test stand and test component has occurred, corresponding sample data transmittal, analysis, and storage is performed. Component test runs are then conducted using healthy components for baseline data. This is normally followed by faulted component baseline runs for faulted data. This process develops a known baseline for the test stand with healthy components and initial baseline data for faulted components to demonstrate signal variability and allow for fault progression traceability. Data comparisons of test specimens that were previously monitored onboard field aircraft are also performed. This is the case for both healthy and faulted components. An example of baseline data for a faulted component both on-board an aircraft and installed on the test stand is provided in figures 23–26.

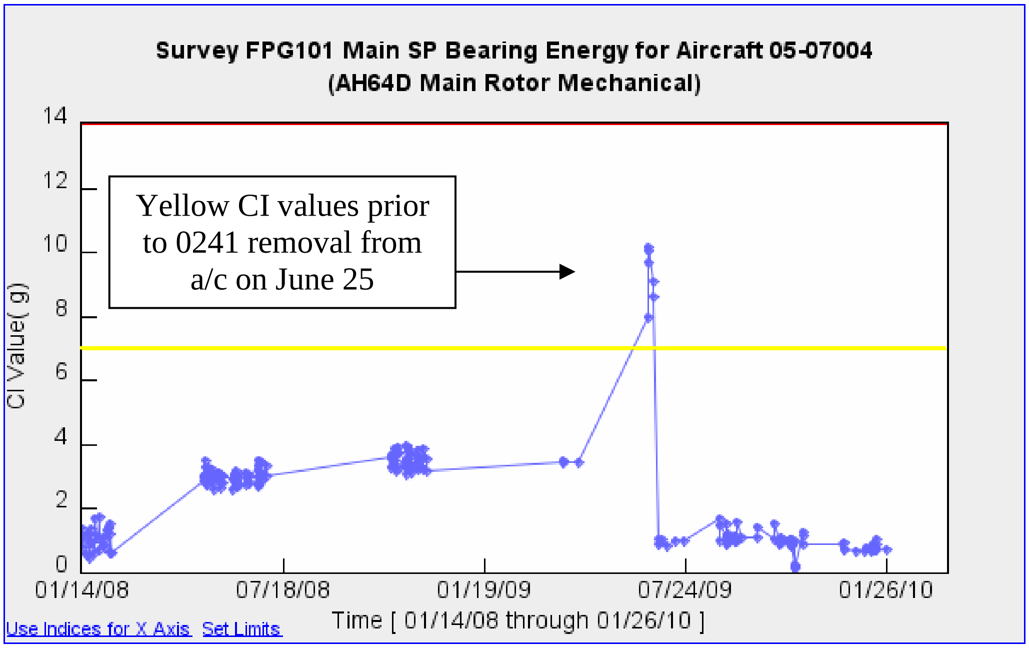


Figure 23. MRSP BE CI trend for 0241 onboard aircraft

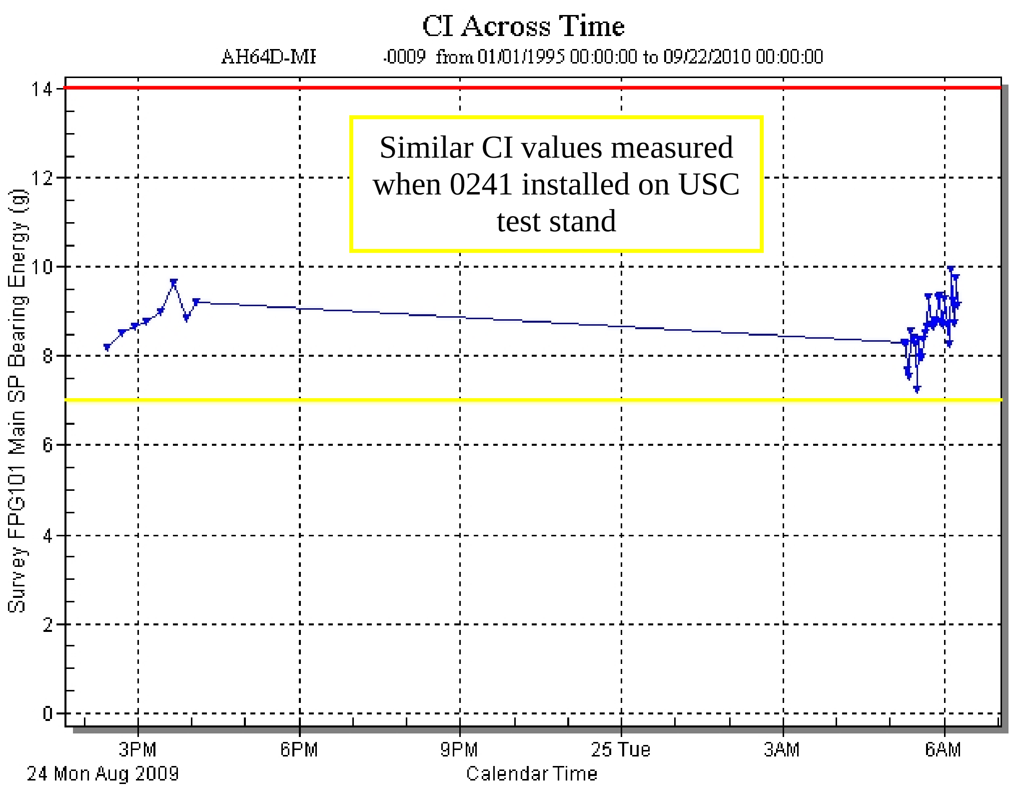


Figure 24. MRSP BE CI trend for 0241 on test stand

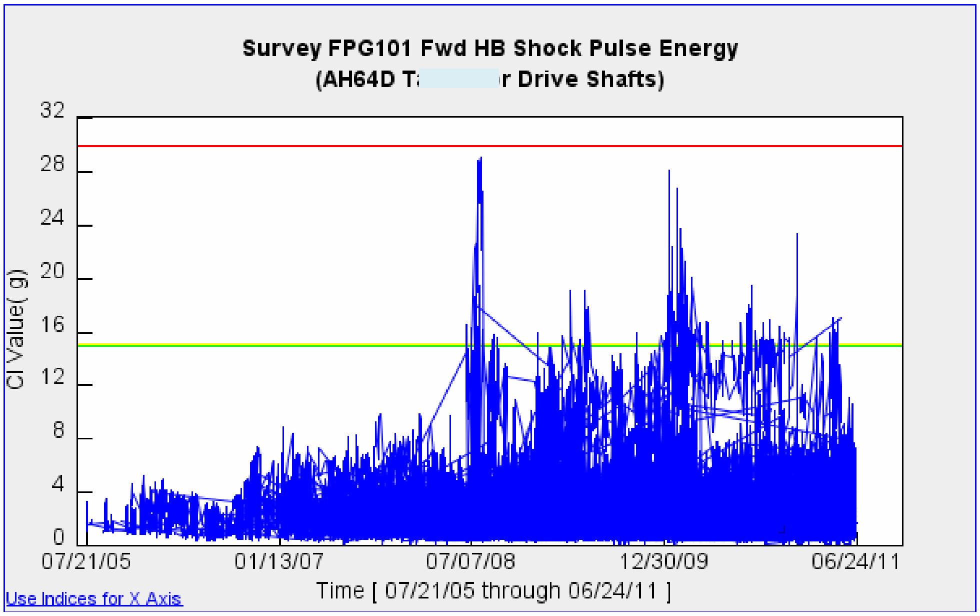


Figure 25. TRDS hanger BE CI on board all fleet aircraft

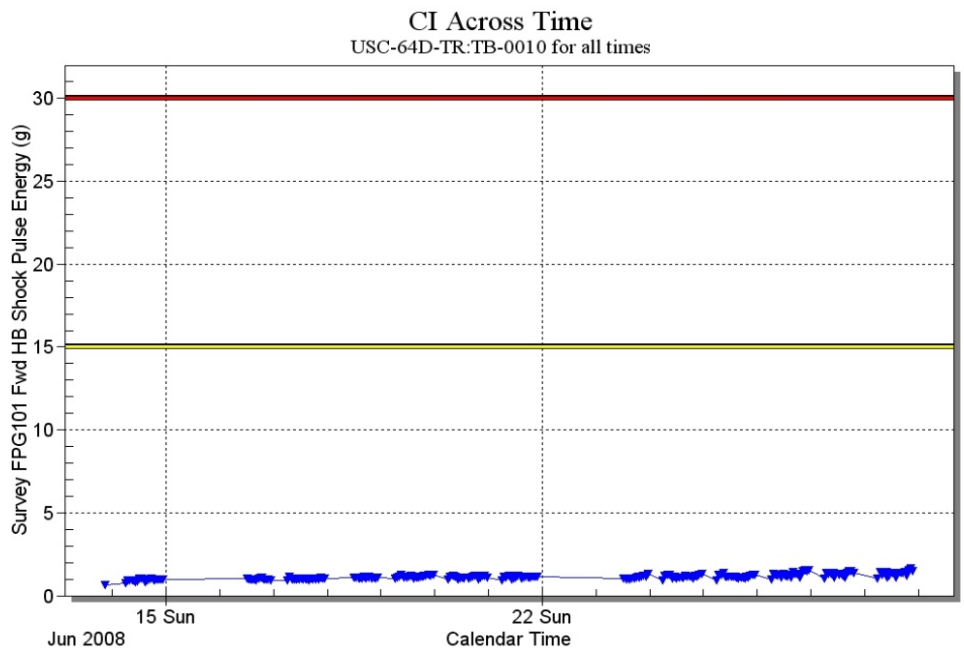


Figure 26. TRDS hanger BE CI for AED-003 on USC test stand

3.4.3.1 ARL Baseline Signature for the TRDS Hanger Bearing Test

Baseline vibration levels for the first ARL TRDS hanger bearing test stand resulted in unexpected high vibrations (20 g) on a single bearing as the rig approached the desired operating speed [22]. This was later resolved with the introduction of stiffening plates. Subsequently, six new bearings were baselined on the ARL test stand. All faulted bearings were then baselined and tracked for fault progression.

3.4.3.2 USC Baseline Signature for the MRSP and TRDS Hanger Bearing Tests

A baseline signature for the MRSP bearing (unmodified original) assemblies to be used in future USC seeded fault testing was established by installing and running them at FPG101 (101% rotor speed and flat pitch ground torque load) on the USC MRSP test stand. This allows for the ability to collect baseline signatures of the original MRSP assemblies. A minimum of 30 samples of monitor-mode CIs on each MRSP assembly is required to establish a baseline. The baseline test of a given MRSP assembly must precede any fault seeding work by RTC on that MRSP assembly. Initially, two MRSP assemblies are used in the fault seeding process to create the MRSP UUTs listed in table 10.

The USC TRDS hanger bearing test stand baseline signatures established a reference using five new (unfaulted) hanger bearings. Testing was performed in the FPG101 simulated aircraft ground condition on the USC test stand prior to the start of formal seeded fault testing. At least 30 samples of spectral and CI data on each bearing were required to establish the baseline.

Initial vibration and temperature readings of the seeded hanger bearings were taken at the beginning of the test run. The CIs and raw data were recorded if the fault was detectable. If the fault was not detectable in the initial signature, then the hanger bearing was run until the fault was detectable or for 100 hours, whichever was less.

Baseline vibration levels measured on both the USC MRSP and TRDS hanger bearing test stands were lower than the normal range for fleet aircraft. This was expected because of the stands not having additional vibration and noise sources that are present on fleet aircraft. CI values and deviation are typically greater on aircraft than on a test stand. However, vibration levels measured for faulted test articles on the USC stands responded similarly to levels from verified cases of MRSP and TRDS hanger bearing faults on fielded MSPU-equipped aircraft. Therefore, though green-condition CI values from the stand do not directly match values across the fleet, testing revealed the CIs do trend and reach fault alert threshold values similar to that which occurs on an aircraft.

4. TEST EXECUTION ACTIVITIES

The general activities executed throughout the testing after baseline data were collected are discussed in this section. Testing on board the AFTD test aircraft is not addressed in this section because this was a brief and relatively simple seeded fault test conducted to obtain a small data set of vibration signatures. An overview of the test activities for the AFTD aircraft test is provided in reference 22. In addition, since the ARL test stand activities were accomplished independently from AED, the ARL test stand activity is also not specifically discussed. However, the reports in reference 20 should provide a beneficial understanding of the test activities encountered by ARL, as reported by ARL personnel.

With respect to the USC test stands, the AED seeded fault test IPT meets weekly to survey the progress of testing the MRSP and TRDS hanger bearing specimens with USC. Typically, the USC test stands sustain 40–50 hours of test runs each week. The TRDT test stand is normally run in parallel with the MRSP test stand. Test stand data are reviewed to track fault progression and discuss any anomalous signals. Test stand maintenance issues arise approximately two to three times a year requiring the test stand to be shut down from 1–2 months. Smaller issues—such as failed accelerometers and broken transmission lines—are also encountered, requiring one half to a full day to rectify and reestablish an agreed point in time for the test stand load profile.

After the current status is reviewed, the IPT then addresses the specimen test run order previously established at the TRR, and preparation for future specimens is undertaken. The test specimen run order modifications evolve during the life of the MRSP test project. The order is based on the test results of previously tested UUTs but is coordinated prior to any revision to the run order. This is also the case for test plan amendments and any potential test stand modifications that may have ramifications on previously collected data.

4.1 USC TEST EXECUTION FOR THE MRSP BEARING

In executing the USC MRSP bearing test plan [17], a series of 50-minute pitch loading steps were designed to simulate MRSP cyclic loads and help accelerate non-conforming component fault propagation. The MRSP cyclic loading profile is provided in table 11.

Table 11. MRSP operating pitch link load profiles

Elapsed Run Time (hh:mm)	Main Rotor Speed (RPM)	Pitch Link Loading (lb)
00:00 – 00:10	292	0*
00:10 – 01:00	292	100
01:00 – 01:10	292	0*
01:10 – 02:00	292	150
02:00 – 02:10	292	0*
02:10 – 03:00	292	200
03:00 – 03:10	292	0*
03:10 – 04:00	292	250
04:00 – 04:10	292	0*
> 04:10	MSPU Downloaded	MSPU Downloaded

* FPG101 survey window

To minimize static loading damage to ball bearings, the pitch link loading is removed when a delay of more than four hours is expected between run cycles. Once an MRSP bearing UUT is installed in the test stand, it is not expected to be removed for at least 50 hours to propagate an increase in the fault condition. At the end of each 50-hour test period, the IPT reviews the data in detail and comes to one of the following determinations:

- Continue testing for another 50 hours
- Terminate the testing of that UUT
- The UUT has reached a point of imminent failure
- The test plan is terminated at the discretion of the IPT

Initial vibration readings of the UUT, taken at the beginning of the test cycle, provide CIs and spectral data of the beginning (Test Time = 0 hours) condition. CIs and Yellow/Red threshold exceedance levels are approved by the AED Aeromechanics Division prior to testing and are identical to the diagnostics in software setup version 75 for the aircraft MSPU.

At the end of each 100 hours of testing, the IPT again reviews the data to determine whether to continue running the UUT or move on to the next specimen. This decision is based on the progress/promise of signal fault progression for the particular component and the budget constraints which were initially set using an estimate of 100 hours per specimen.

The progression of specimen selection for the USC MRSP bearing test stand was executed using the flow process outlined in figure 27.

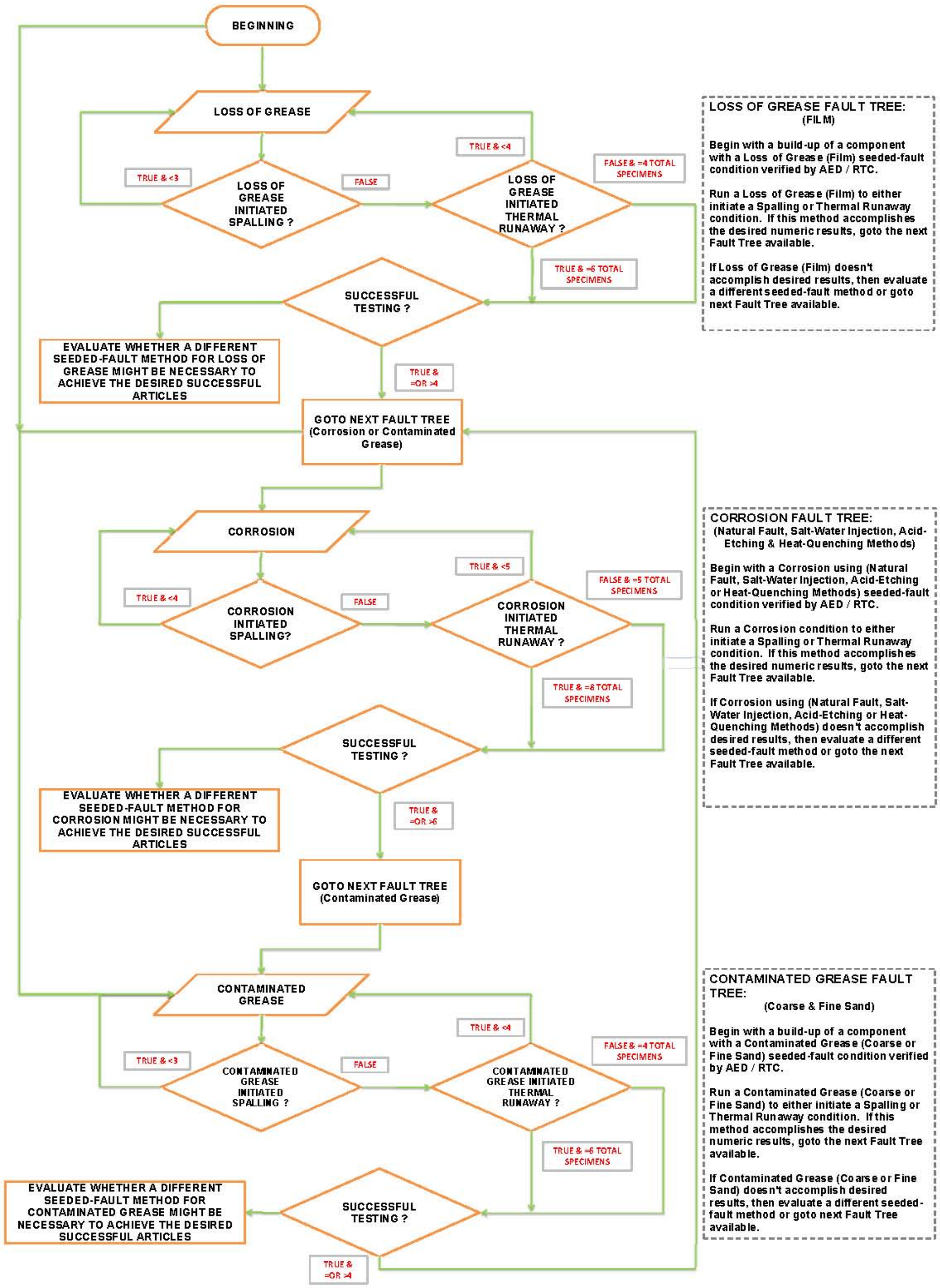


Figure 27. MRSP test stand flow chart

4.2 USC TEST EXECUTION ACTIVITIES FOR THE TRDS HANGER BEARINGS

The USC TRDS hanger bearing seeded fault test plan [25] was executed in a progression, as shown in figure 28. Figure 28 was updated for this report and reflects actual test events. The test hours stated for a test cycle (see figure 29) were not required to run consecutively and did not require non-stop 24-hour operations. The cycles were broken into smaller intervals based on the normal hours of operation of the test facilities.

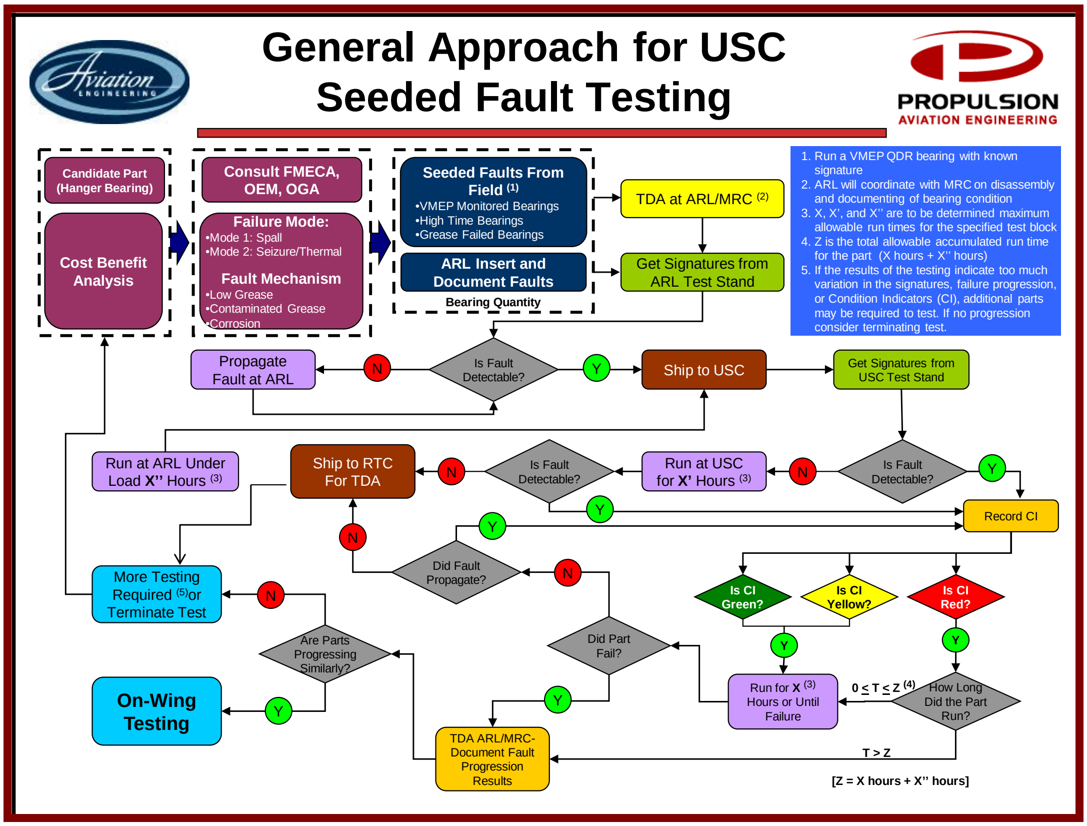


Figure 28. General approach for USC TRDS hanger bearing seeded fault testing

Run Time	Time Fraction	RPM	Bearing Flange Torque	Tail Rotor Output Torque	Rated Power Level	MSPU Data Type Collected
0:00-0:10	4%	4863	32	111	9%	Survey
0:10-1:00	20%	4863	108	371	30%	Monitor
1:00-1:10	4%	4863	32	111	9%	Survey
1:10-2:00	20%	4863	214	734	60%	Monitor
2:00-2:10	4%	4863	35	111	10%	Survey
2:10-3:00	20%	4863	311	979	87%	Monitor
3:00-3:10	4%	4863	32	111	9%	Survey
3:10-4:00	20%	4863	356	1223	100%	Monitor
4:00-4:10	4%	4863	32	111	9%	Survey

Figure 29. USC TRDS hanger bearing test cycle

CI and threshold exceedance levels were approved by the AED Aeromechanics Division and identical to the hanger bearing diagnostics in software setup version 48 for the aircraft.

The first test specimen from each fault mechanism to initiate a spall or seizure failure mode was intended to be run to failure. AED monitored the resulting vibratory and thermal data from each of these test specimens designated for testing to failure and provided test termination criteria. In addition, AED Engineering monitored the testing progress at each X and X' interval (see figure 28) to determine if testing should continue at the USC test facility or if the bearing should be transferred to RTC for TDA.

Subsequent hanger bearing test specimens were evaluated on a case by case basis by AED Engineering after initially running on the USC test stand for X' = X = 100 hours (this was later modified to 50 hours). AED Engineering also monitored the resulting vibratory and thermal data and provided recommendations for termination of each test on a case by case basis. After a detectable fault was noted at USC by the recorded CIs and raw data, the IPT directed continued testing for a period of 100 hours or until failure. At the end of the additional 100 hours of testing, AED reviewed the data to determine whether to ship the bearing to RTC for TDA continue running for another 100 hours at USC, or terminate the testing for the specimen.

5. TEST TERMINATION

Eventually, there is a point at which the seeded fault testing must be stopped. This section outlines the test termination conditions used by the U.S. Army during seeded fault testing of the MRSP and TRDS hanger bearings.

In regard to the on-aircraft testing for both the MRSP and TRDS hanger bearings, the AFTD aircraft seeded fault test termination was evident by AED's test plan [20] completion of two 75-minute data acquisitions.

ARL hanger bearing seeded fault test termination, however, was more obscure because their tasks were to: (1) experiment with seeded faults to see if the CIs programmed in the MSPU would respond to the failure modes that are simulated by seeded faults; (2) establish a baseline for comparing vibration signature data from bearings with laboratory seeded fault conditions; and (3) accelerate wear on bearings, through various mechanisms, for use on the USC test stand. ARL's primary termination constraints were time and money. Whatever the outcome from ARL testing, the ARL seeded fault bearings were intended to be sent to USC for continued testing.

Termination guidelines for USC testing on the MRSP and TRDS hanger bearings are more complex and relied on the final determination of the AED seeded fault IPT. The details of these guidelines (see appendix B and reference 17) are provided in sections 5.1 and 5.2.

5.1 TEST TERMINATION GUIDELINES FOR USC MRSP BEARING TEST STAND

During USC MRSP bearing fault progression testing, the following guidelines were used to terminate the MRSP bearing seeded fault test. For all cases listed, the testing was suspended and the condition reported to AED for consideration prior to any further action:

Case 1 – Unsafe Condition:
The USC test conductor may stop the test at any time that the fault progression is deemed to be unsafe, with potential to damage the test stand or injure personnel.

Case 2 – Fault Detected But Not Progressing:
For MRSP components which have detectable damage, but the fault does not show signs of propagating after 50 hours of test stand operation, the IPT will make a decision whether to continue the test or terminate it.

Case 3 – Excessive MSPU Condition Indicator:
The USC test conductor may stop the test if the MSPU identifies the MRSP as a Red condition and the IPT will be notified and make a decision whether to continue the test or terminate it.

Case 4 – Exceedance Detected by Sensors Other Than MSPU:
For MRSP components which exceed the following limits as measured on the USC facility instrumentation:

- **Horsepower**: input HP is greater than 15% or 15 HP (whichever is greater) above the output HP for a given loading
- **Vibration**: 5 IPS

Case 5 – Failure of Test Article:
The test article fails or reaches a point of imminent failure or another component on the test stand fails.

Case 6 – No Sign of Fault Progression:
If a test article is run for 500 hours without high temperature, vibration, or other signs of fault, the IPT will decide whether to continue or terminate the test.

5.2 TEST TERMINATION GUIDELINES FOR USC TRDS HANGER BEARING TEST STAND

During USC TRDS hanger bearing fault progression testing, the following guidelines were used to terminate the TRDS hanger bearing seeded fault testing. For all cases listed, the testing was suspended and the condition reported to AED for consideration prior to any further action:

Case 1 – Unsafe Condition:
Testing was stopped at any time when the USC test director deemed the tail rotor drive shaft test stand was unsafe to operate.

Case 2 – Fault Detected But Not Progressing:
For bearings which have detectable damage, but the fault does not show signs of propagating within 100 hours of test stand operation, the AED/USC/ARL test team will make a decision whether to continue, return the bearing to ARL for additional run time, or terminate the test.

Case 3 - Excessive Shaft Vibration:
VMEP MSPU equipment detects a Shaft Order One (SO1) indicator exceeding 5 IPS (the normal aircraft condition is 2 IPS).

Case 4 – Exceedance Noted by Sensors Other than VMEP MSPU:
For bearings which exceed the limits of the USC DAQ facility instrumentation:

- **Torque**: 3x baseline drive train drag torque (as measured between the input motor and the IGB-input)
- **Temperature:** 40 degree F above normal steady state temperature of baseline bearings
- **Vibration:** 5 IPS

Case 5 – Failure of Test Components:
The test was terminated if the test article failed, reached a point of imminent failure, or a portion of the test rig failed.

6. DATA ANALYSIS & TEST RESULTS

The U.S. Army requires two resultant elements for confirmation of a fault on the MRSP and TRDS hanger bearings. This could be from a monitored field aircraft or a seeded fault test stand. These confirmations are either threshold alerts from CI/HI data or direct evidence from a TDA. The seeded fault test facility provides the CI/HI data; RTC accomplishes the post test, physical inspection, and teardown investigation; and the analysis of the teardown results is performed by AED. AED then color rates (see table 6) the hardware on the basis of component condition by an experienced drive train and dynamic component group of engineers and technicians. Once this is completed, the vibration data recorded from the test facility is analyzed by the AED Aeromechanics Division vibration experts and compared to the rated component condition. MSPU software CI/HI algorithms and threshold alerts are then either reevaluated or created by the AED Aeromechanics Division for potential fleet software modification. The AED Propulsion Division also determines applicability of the data point toward achieving validation of any maintenance credits for legacy maintenance modification/replacement.

The AED Aeromechanics Division analysis of algorithms and alerts or the AED Propulsion Division analysis for maintenance credits both require a different approach to process the data from seeded fault testing.

For validating current CIs/HIs during seeded fault tests, it is necessary to post-process test data to ensure the test stand is representative of the field aircraft using healthy and faulted components. This data processing is accomplished by the AED Aeromechanics Division with baseline run data similar to that illustrated in figures 23–26. If the processed fault data generate similar signals to the known field faults and trigger the correct MSPU alerts, then it is accepted as a data point for validating the CI/HI. The seeded fault data point is also recorded as potential data for validating a maintenance credit applied to modify or replace legacy maintenance.

If seeded fault testing is pursued in an exploratory manner to establish an initial CI/HI, baseline run and data processing is still necessary for both healthy and faulted components to understand the vibration signal differences. Exploratory testing is performed to evaluate prototype CI algorithms and thresholds not yet fielded; sensor performance; and/or how different fault types progress over time. Because most exploratory testing is completed when there are little to no examples of fielded faults and a CI may not yet be created, there is initially sparse field fault data to compare against seeded fault test stand data. Such was the case for both the MRSP and TRDS hanger bearings when seeded fault testing initially commenced. However, the last few years have produced additional data for analysis from the seeded fault test stands, which are discussed in sections 6.1 and 6.2.

6.1 MRSP BEARING DATA ANALYSIS AND RESULTS

Because the MRSP bearing seeded fault testing is currently ongoing, MRSP bearing post-test data results have yet to be provided in a formal USC summary document for final AED analysis. The MRSP bearing test stand data are currently recorded on the USC server and the data were delivered to the U.S. Army for the four specimens that have completed testing to date.

The following is a synopsis of the seeded fault specimen testing completed to date, including S/Ns, for the MRSP assemblies:

- MRSP assembly S/N 0888 was initially tested as a healthy baseline component on the AFTD aircraft in accordance with reference 20. The swashplate was removed from the aircraft and #540 coarse sand was added to the bearing. Over 400 hours of testing were sustained on the test stand by the bearing in this assembly, with a slight elevation in the BE CI. The CI later dropped to normal levels before the specimen was removed from the test stand.

- MRSP assembly S/N 0363 was tested with only a thin film of grease on the bearings but endured over 700 hours of testing without elevation in any of the CIs measured before it was removed from the test stand because of CI inactivity.

- MRSP assembly S/N 0390 was tested with only a thin film of grease on the bearings and the test halted at just over 200 hours of testing because of a bearing thermal runaway event that developed over approximately five hours at the end of testing.

- MRSP assembly S/N 0241 was tested with field-induced static corrosion on the bearing races and sustained less than 50 hours of testing before it was removed from the test stand. This swashplate was removed because it was only used as a baseline specimen to compare CI data between the field and the USC test stand.

Figures 30–33 are sample CI plots for BE experienced by the above MRSP swashplates on the USC test stands.

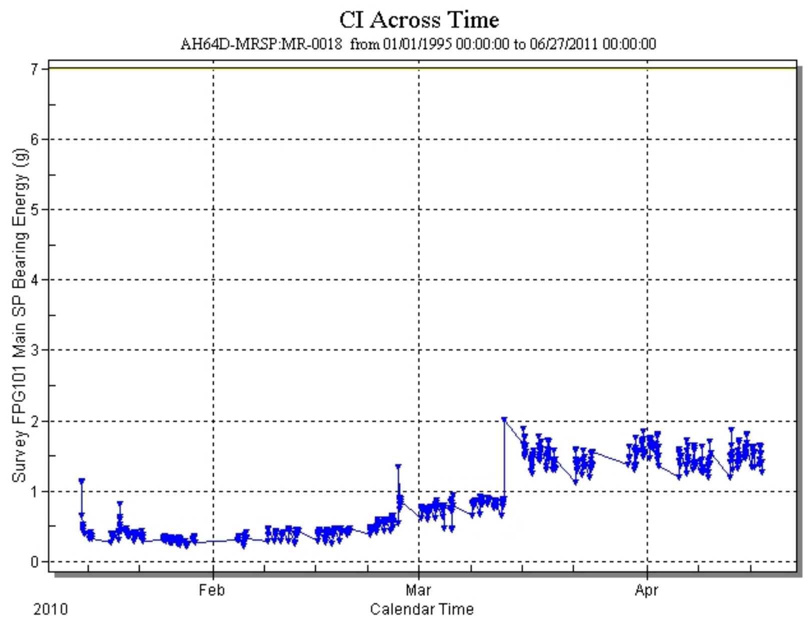


Figure 30. MRSP assembly S/N 0888 CI plot on USC test stand

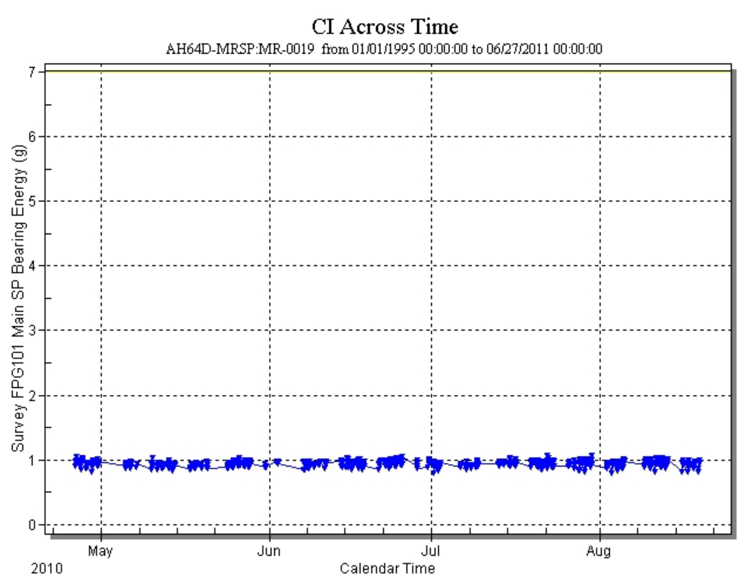


Figure 31. MRSP assembly S/N 0363 CI plot on USC test stand

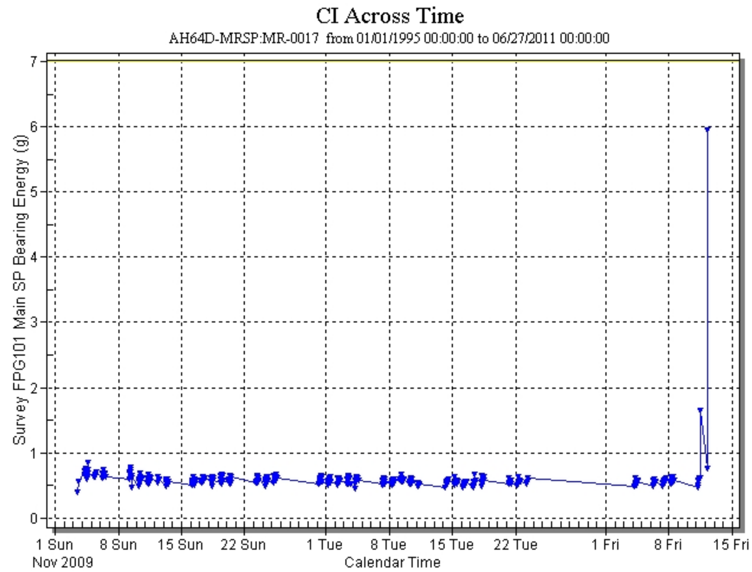


Figure 32. MRSP assembly S/N 0390 CI plot on USC test stand

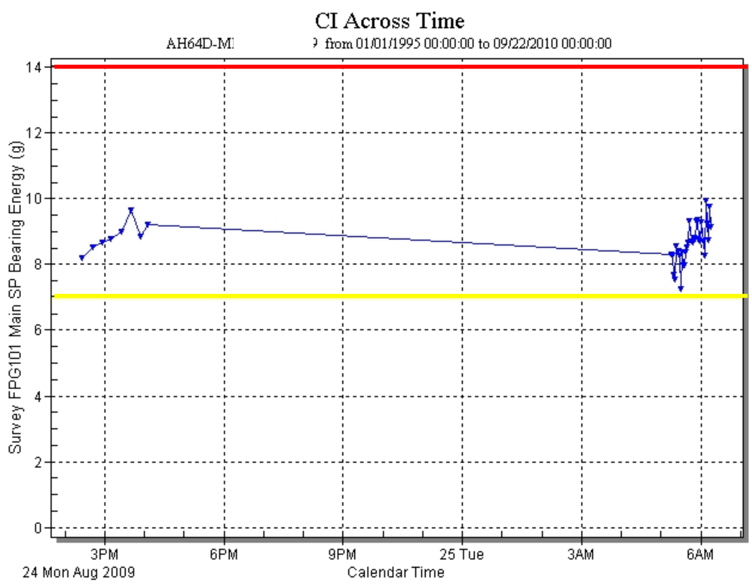


Figure 33. MRSP assembly S/N 0241 CI plot on USC test stand

Subsequent to receipt of the USC data and RTC TDAs for the MRSP bearings, AED performed their engineering analyses and determined the hardware condition and color code ratings, as displayed and defined in table 6:

- Green: MRSP bearing with 540 coarse sand (S/N 0888)
- Green: MRSP bearing with thin film grease (S/N 0363)
- Red: MRSP bearing with thin film grease (S/N 0390)
- Yellow: MRSP bearing field induced static corrosion (S/N 0241)

To date, no statistical analysis has been conducted for the MRSP bearing to determine the potential for modifying or replacing legacy maintenance practices. This is because of the lack of statistically significant data available to perform an analysis, which requires a 90% confidence level with 90% reliability. Meanwhile, MRSP bearing seeded fault test data will continue to support CI maturation, provide QDR submittals, and enhance legacy maintenance practices via trend analysis for early component removal decisions to reduce secondary damage. However, additional data from ongoing tests may change this course of action.

6.2 TRDS HANGER BEARING DATA ANALYSIS AND RESULTS

For the ARL TRDS hanger bearing seeded faults, TDAs were performed on the ARL hanger bearings after they were sent from ARL and tested on the USC test stand. AED also supplied bearings directly to USC to increase the number of bearings to be tested. The post-test, USC test article summary with CI plots and associated RTC TDA documentation for the ARL and AED supplied bearings may be found in reference 26. The USC test article summary incorporates a reference chart with several other bearing S/Ns not addressed. The USC hanger bearings in reference 26 that are not addressed in this section were not monitored and were used as baseline bearings without seeded faults or incorporated as a test stand asset to allow the stand to operate.
The following information provides a synopsis of the completed TRDS hanger bearing seeded fault specimen testing, including S/Ns or other unique identifying numbers:

- TRDS aft hanger bearing S/N 1244U (AED-001) was tested with a cut grease seal to allow grease to leak and then run for 717 hours on the USC test stand. The CI values never exceeded the Yellow or Red thresholds during 5335 data points before the bearing was removed from the test stand because of CI activity not increasing as intended.

- TRDS aft hanger bearing S/N JC53 (AED-002) was tested with a cut grease seal to allow grease to leak and run for 494 hours on the USC test stand. The CI values never exceeded the Yellow or Red thresholds during 3227 data points before the bearing was removed from the test stand because of CI activity not increasing as intended.

- TRDS forward hanger bearing S/N 217UU (AED-003) was tested with a cut grease seal to allow grease to leak and run for 717 hours on the USC test stand. The CI values never exceeded the Yellow or Red thresholds during 5335 data points before the bearing was removed from the test stand because of CI activity not increasing as intended.
- TRDS aft hanger bearing S/N 1311 was tested with a reduced charge of grease on the bearings, run at operating speed for 1270 hours at 295°F and 325 hours at 315°F at ARL, and then run 1501 hours on the USC test stand. The CI value for BE never exceeded the Yellow or Red thresholds. Only the shock pulse energy CI crossed the Yellow threshold. The thermocouple readings for this bearing tended to stay level or decrease through the testing at USC before it was removed from the test stand because of CI activity not increasing as intended.

- TRDS forward hanger bearing S/N 1320 was tested with a reduced charge of grease on the bearings and salt water corrosion, run at operating speed for 370 hours at 295°F and 325 hours at 315°F at ARL, and then run 1501 hours on the USC test stand. The BE CI values never exceeded the Yellow or Red thresholds. Only the shock pulse energy CI marginally exceeded the Yellow threshold. The thermocouple readings tended to stay level or decrease through the testing at USC before it was removed from the test stand because of CI activity not increasing as intended.

- TRDS aft hanger bearing S/N 8522C (ARL-012) was tested with fine sand contamination on the bearings and run 301.8 hours on the USC test stand. The CI readings tended to stay level or decrease through the testing at USC before the bearing was removed from the test stand because of CI activity only exceeding the Yellow alert threshold 63 times out of 2298 data points, followed by a decrease in CIs. The thermocouple readings for this bearing also tended to stay level or decrease through the testing at USC.

- TRDS aft hanger bearing S/N JQ16 (SN Test 1 & ARL-006) incorporated a machined spall on the outer race that was 0.031″ in diameter and 0.015″ in depth. This bearing was also tested at ARL by running it at operating speeds for 902 hours at 295°F and then running it for 899 hours on the USC test stand. The bearing was removed from the USC test stand because of CI activity never exceeding the Yellow or Red alert thresholds. The thermocouple readings for this bearing tended to stay level through the testing at USC. Note that the RTC TDA did not document any damage to the outer race.

- TRDS forward hanger bearing S/N 1303 (ARL-017) was tested with a reduced charge of grease at ARL for an undocumented duration and then run 1501 hours on the USC test stand. The CIs showed steadily increasing shock pulse energy; however, the final value was less than two times the magnitude of the starting value. This bearing was removed from the USC test stand because of CI activity sporadically exceeding the Yellow threshold six times and the Red threshold three times in 3223 data points, which was subsequently followed by a decrease in CIs. The thermocouple readings for this bearing tended to stay level or decrease through the testing at USC.

- TRDS forward hanger bearing S/N 6163Z1 was received from CCAD Storage, Analysis, Failure Evaluation and Reclamation after being removed from a field aircraft with no seeded fault and was run 900 hours on the USC test stand. The CIs showed only a moderate increase in shock pulse energy while all CIs remained below established thresholds. The thermocouple readings for this bearing also tended to stay level throughout the testing at USC. As a result of the CI inactivity, this bearing was removed from the USC test stand.

- TRDS forward hanger bearing S/N 1348 (ARL-021) was seeded with a saltwater corrosion fault by ARL and then run for 355 hours on the USC test stand. The CIs were statistically higher than average. Both the BE and shock pulse energy CI thresholds were consistently above the Yellow/Red exceedance limits. For all CIs, the exceedance count was 329 times for Yellow thresholds and 780 times for Red thresholds in 1771 data points. The thermocouple readings for this bearing tended to stay level and actually decreased near the end of testing at USC. The amplitude demodulated (AMD) bearing CI, which generally has values of less than 1, were in the 2–7 range for this specimen. The results of this specimen and ARL-022 suggest the AMD bearing CI threshold may be lowered for the field.

- TRDS aft hanger bearing S/N 1293 (ARL-022) was seeded with a saltwater corrosion fault by ARL and then run for 355 hours on the USC test stand. The CIs were statistically higher than average and both the BE and shock pulse energy CI thresholds were consistently above the Yellow/Red exceedance limits. For all CIs, the exceedance count was 551 times for Yellow thresholds and 547 times for Red thresholds in 1782 data points. The thermocouple readings for this bearing tended to stay level and actually decreased near the end of testing at USC. The AMD bearing CI, which generally has values of less than 1, were in the 2–7 range for this specimen. The results of this specimen and ARL-021 suggest the AMD bearing CI threshold may be lowered for the field.

Following receipt of the ARL summaries, USC summaries, and RTC TDA documentation, AED performed engineering analyses based on the documentation for the TRDS hanger bearings to determine the following hanger bearing condition, with color code ratings displayed and defined in table 6:

- Green: Hanger bearing with cut grease seal (1244U AED-001)
- Green: Hanger bearing with cut grease seal (JC53 AED-002)
- Green: Hanger bearing with cut grease seal (217UU AED-003)
- Green: Hanger bearing exposed to heat-degraded grease and reduced grease (1311)
- Green: Hanger bearing exposed to heat-degraded grease and salt water corrosion (1320)
- Green: Hanger bearing contaminated with fine sand (8522C ARL-012)
- Green: Hanger bearing exposed to heat-degraded grease and machined spall (JQ16 ARL-006)
- Green: Hanger bearing with reduced grease (1303 ARL-017)
- Green: Hanger bearing removed from a field aircraft (6163Z1)
- Red: Hanger bearing corroded with saltwater (1348 ARL-021)
- Red: Hanger bearing corroded with saltwater (1293 ARL-022)

The AFTD, ARL, and USC hanger bearing test durations were conducted through the early part of 2011. Based on the data received to date, the U.S. Army PMO for the helicopter requested that AED consider the possibility of extending hanger bearing time on wing beyond the 2750-hour time change requirement while staying below the 6487-hour bearing flange fatigue life. This request was made prior to completion of the USC hanger bearing seeded fault test program. Note also the TRDS hanger bearing test plan was designed to obtain sufficient faulted samples to establish statistically significant results. Statistical significance was quantified using 90% confidence and 90% reliability on the monitoring CIs in accordance with using the following Clopper Pearson statistical methodology [4]:

[sample size for zero cases of incorrect CI classification = ln (1-Confidence) / ln (reliability)]

To attempt to meet the PMO's request with the data obtained to date, AED applied an alternate methodology to demonstrate statistical significance based on a Weibull statistical analysis incorporating a Weibull beta value of 1.1. This alternate approach also required reference to the following documents to enable authorization for extended hanger bearing time on wing beyond the current flight hour calculations for five-year grease life:

- ASTM standard 3336-05, "Standard Test Method for Life of Lubricating Greases in Ball Bearings at Elevated Temperatures," ASTM D 3336-05 [27].
- Honeywell Incorporated Report, "U.S. Army – COSSI Program: Power Transfer Clutch for Models 36-55 and 36-155 APUs Used on the Helicopter – Primary Bearing Grease Life Test Report" [28].
- Booser, E.R., "Grease Life Forecast for Ball Bearings," Lubrication Journal [29].
- Booser, E.R., "Life of Oils and Greases," Tribology Data Handbook [30].
- ExxonMobil Grease Experts for Mobil 28.

Using 90% grease life reliability (i.e., L10 grease life) with 90% confidence, eight ARL/USC test specimens were required to have accumulated an average run time of 8100 hours each to achieve authorization for a 500-hour increased time on wing beyond 2750 hours. Both ARL and USC seeded fault data from accelerated lifing conditions with heat-degraded grease were used for this exercise. The U.S. Army then introduced the grease life acceleration factors for both the generic grease life testing performed in reference 28 and the Booser grease life equations in references 29 and 30 to the seeded fault data. The U.S. Army determined the amount of actual hanger bearing test hours averaged an equivalent 8314 hours per tested bearing for 10 bearings at the normal bearing operating temperature. This amount of endurance testing resulted in an acceptable grease life calculation of 4104 hours with 90% reliability and 90% confidence, as shown in appendix C.

Because of the relatively low load carried by the hanger bearings in normal operation, the calculated L10 life of the bearing design is over 100,000 hours even before the application of material and lubrication life factors, which would increase the calculated life.

Therefore, the heat-degraded grease, seeded fault testing, calculations, and bearing fatigue life calculations supported a bearing time on wing extension to 3250 hours when considering grease life and rolling contact fatigue assuming 90% reliability and 90% confidence.

Furthermore, discussions between AED and representatives from ExxonMobil (the hanger bearing grease manufacturer) revealed that, typically, grease is assumed to have a five-year shelf life because of the potential for oil-thickener separation. Originally, this assumed shelf life, along with the operational flight hour tempo of the U.S. Army helicopter, was used to determine the 2750-hour time change requirement of the bearing. However, ExxonMobil stated, for the case of sealed bearings like the hanger bearings, the calendar-based degradation assumption does not apply provided the seal is maintained, routine visual grease leakage inspections are conducted, and contamination is prevented. In an assembly, such as the hanger bearings for this helicopter, operating temperature is the primary factor in grease degradation.

The L10 life of the grease in the hanger bearings, with temperature as the primary concern, is estimated to be a minimum of 6000–6500 hours. The accelerated grease life testing at USC demonstrated that a hanger bearing with degraded/contaminated grease was capable of operating satisfactorily for a minimum of 3250 hours beyond the point of grease degradation that would be expected after 6000–6500 operational hours. Together, these two pieces of information also helped support the technical basis for a hanger bearing time change extension beyond 2750–3250 flight hours.

As a result, AED developed sufficient evidence between the ARL/USC testing and grease life calculations to recommend extending the retirement life for both monitored and unmonitored hanger bearings to 3250 hours provided the bearings continue to be inspected for grease leakage at each 250-hour periodic inspection as currently specified in maintenance manuals. This extension was based on endurance testing.

Subsequent to the AED approval for 3250 hours on the hanger bearing, the AED risk analysis team analyzed two hanger bearing CIs to determine if a Weibull distribution could be found to fit each set of CI data. With a good fit for a Weibull distribution found, a minimum sample size needed to be calculated that could meet the 90% confidence and 90% reliability requirements specified in the ADS-79 Handbook [4].

The specific hanger bearing CIs analyzed for a Weibull distribution were dual-band energy (DBE) and BE. These CIs are calculated on board the aircraft as part of an automatic data capture (survey mode) once per flight while the aircraft drive system is operating at speed on the ground. The CI values were taken from 22 hanger bearings documented in this report and reference 28, representing a mixture of forward and aft bearings. The data set represents both test stand and fielded aircraft readings. Using the scorecard in table 6, three of the 22 hanger bearings were confirmed to be condition Red; the remaining 19 bearings were confirmed to be condition Green.

For each bearing and CI, the time and date were recorded whenever a CI measurement was taken. This analysis grouped CI data from consecutive measurements that were taken within six hours of each other; when consecutive measurements were taken in intervals greater than six hours, a new group was started. For each bearing and CI, the median CI values were calculated for the last (most recent) group of measurements. Because the aircraft displays the last value of the vibration survey, the median value calculated serves as an added level of conservativeness for the field. The maximum value was a peak-pick method used for comparison. The resulting four CI datasets, DBE_{med}, DBE_{max}, BE_{med}, and BE_{max}, are presented in table 12.

Table 12. CI datasets and condition of bearings

Serial No.	Condition	DBE_{med}	DBE_{max}	BE_{med}	BE_{max}
ARL-012	GREEN	3.66	3.85	4.11	4.54
ARL-017-LG	GREEN	1.71	2.13	1.06	1.17
AED-002-LG	GREEN	1.38	1.63	1.71	2.42
AED-003-LG	GREEN	1.37	1.53	1.03	1.58
AED-001-LG	GREEN	2.20	2.90	1.85	2.40
ARL-021	RED	49.47	53.24	10.77	12.11
ARL-022	RED	47.53	48.48	12.43	13.05
6163Z	GREEN	3.17	3.56	1.12	1.23
ARL TEST 1 and ARL-006	GREEN	2.95	7.93	1.86	3.40
2245	GREEN	0.96	1.16	1.68	1.73
0320	RED	40.44	43.95	55.26	69.25
1352	GREEN	2.23	5.81	2.71	3.94
2912	GREEN	48.82	50.46	3.56	3.65
2267	GREEN	30.19	30.93	3.68	3.93
1533U	GREEN	0.37	0.40	1.52	2.20
2296	GREEN	9.12	10.17	1.57	2.11
2144	GREEN	22.60	22.60	2.26	2.26
2132	GREEN	1.28	1.28	2.63	2.63
3044	GREEN	0.91	0.94	2.21	2.39
1964	GREEN	13.51	13.51	2.34	2.34
1311	GREEN	5.25	11.69	0.96	1.34
1320	GREEN	8.97	8.97	1.46	1.46

A Weibull analysis was performed on each CI dataset. Weibull distributions with acceptable fits were identified for DBE_{med} and DBE_{max}. However, an acceptable Weibull fit could not be found for BE_{med} and BE_{max}, so some other methodology must be used to compute the minimum required sample size based solely on the BE CI.

A summary of the Weibull analyses for DBE_{med} and DBE_{max} is provided in table 13.

Table 13. Weibull parameters and threshold for DBE datasets

Dataset	Weibull β	Weibull η	90/90 Threshold
DBE_{med}	8.68	49.34	31.91
DBE_{max}	9.11	52.13	34.51

The Weibull plots for DBE_{med} and DBE_{max} are shown in figures 34 and 35, respectively. For each figure, CI values from Red bearings are depicted on the plot, but CI values from Green bearings are not. The straight line is the Weibull fit, and the curved line to the left is the 90% lower confidence bound. The CI value that provides 90% reliability with 90% confidence (the alert threshold) is found by locating the point where the line reliability = 90 (*y*-axis) intersects with the lower confidence bound line, then reading the point's value from the *x*-axis (DBE CI).

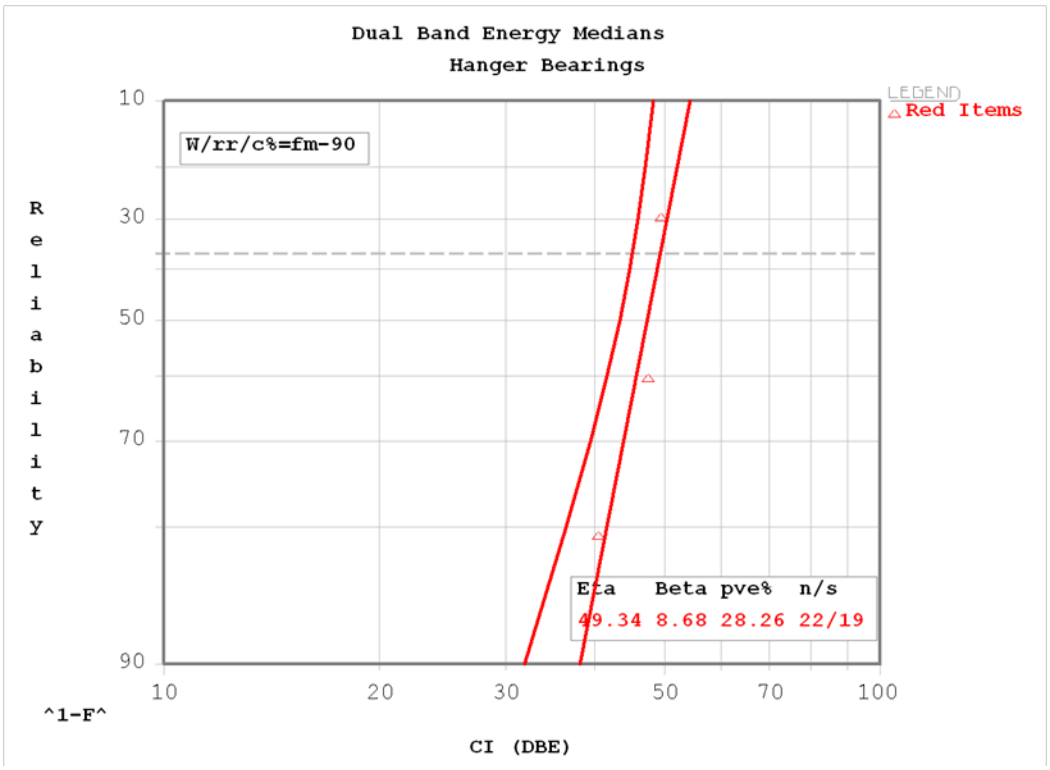


Figure 34. Weibull plot for DBE_{med}

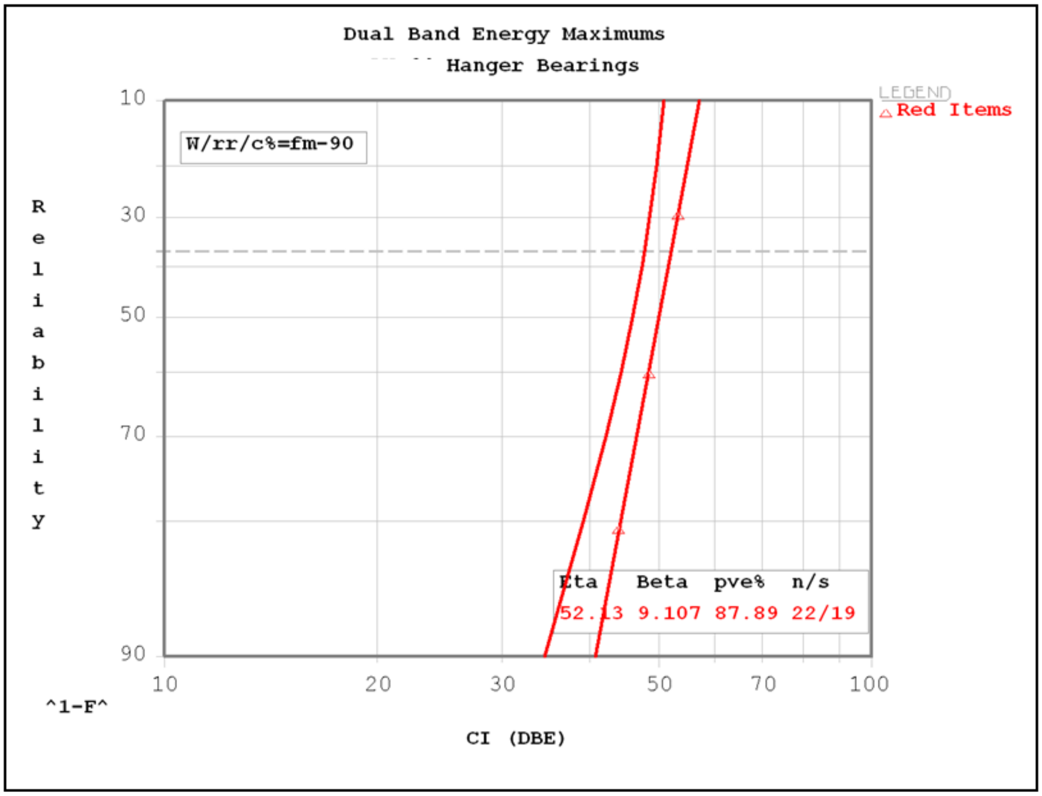


Figure 35. Weibull plot for DBE_{max}

Using the Weibull β values for DBE_{med} and DBE_{max} (see table 13), table 14 provides minimum failure-free sample sizes needed to demonstrate 90% reliability with 90% confidence at a Green/Red threshold of 35.

Table 14. Minimum Sample Size for Threshold = 35

DBE CI value to test to	Minimum Sample Size for CI Threshold = 35	
	DBE_{med}, β = 8.68	DBE_{max}, β = 9.11
35	22	22
40	7	7
45	3	3
50	1	1

Table 15 provides minimum failure-free sample sizes needed to demonstrate 90% reliability with 90% confidence at a Green/Red threshold of 40.

Table 15. Minimum sample size for threshold = 40

DBE CI value to test to	Minimum Sample Size for CI Threshold = 40	
	DBE_{med}, β = 8.68	DBE_{max}, β = 9.11
40	22	22
45	8	8
50	4	3
55	2	2

Because the aircraft method for capturing and storing the CI value is not a peak-pick method (relating to the DBE_{max}), the values used for on-condition analysis and consideration will be DBE_{med}. The initial Red threshold fielded for the CI DBE is 35 g (set initially by standard deviation statistics for data gathering). Table 13 shows that a Red threshold of 31.91 g is the value of the DBE_{med} CI to meet the 90/90 criteria of ADS-79 [4] for replacing legacy maintenance inspections with the MSPU CI. Therefore, using a lower DBE CI threshold of 31.91 g in the MSPU allows for a maintenance credit to be realized. Note that a follow-up fleet analysis was also performed to discern how many hanger bearings on operating aircraft would be required to be pulled for the lower 31.91 g threshold because the lower the threshold is set, the higher the number of false positives will be encountered. Another option would be to use the thresholds and sample sizes notated in tables 14 and 15 (35 g and 40 g, respectively).

For the forward and aft hanger bearings' legacy time change maintenance requirement of 2750 hours to be modified to on-condition maintenance, the following conditions were required to be met:

1. The aircraft must be monitored.

2. The legacy maintenance nutation check every 250 hours must remain in effect.

3. The forward and aft hanger bearing input and output flange fatigue life of 6487 hours must remain in effect.

4. The MSPU must be installed and operating correctly with a DBE Red threshold setting of 31.91 g or lower. In the event the MSPU becomes inoperable and the last reviewed condition of DBE is Green, the respective aircraft will have 50 hours to reestablish the MSPU to an operational status. In the event the aircraft's MSPU does not regain operability, the forward and aft hanger bearings will revert back to legacy maintenance, including requirements for the 2750-hour time change. DA Form 2410 tracking is still required for all forward and aft hanger bearing assemblies, even if the bearing is being maintained based on condition monitoring.

5. The MSPU data for DBE must be downloaded and reviewed for its condition per the current interval of every 25 hours. A Red indication will require the component to be removed and replaced immediately.

6. The fleet data must be audited annually to ensure the threshold of 31.91 g continues to demonstrate 90% reliability with 90% confidence.

The U.S. Army PMO for this helicopter was satisfied with the results of the TRDS hanger bearing data analysis and recently revisited their intent to extend hanger bearing time on wing beyond 3250 hours. However, realization that hanger bearings are turned into depot most frequently for a 250-hour nutation check between the bearing and the bearing housing has convinced the PMO to cease supporting any further extensions.

7. ASSIMILATION OF ADS-79 U.S. ARMY PROCESS/GUIDANCE WITHIN AC 29-2C MISCELLANEOUS GUIDANCE 15

The FAA AC 29-2C Miscellaneous Guidance (MG) 15 [33] provides guidance for airworthiness approval of HUMS on rotorcraft. Under AC 29-2C MG 15 paragraph g(3)(i)(B)(2), the FAA addresses credit validation methodology guidance using direct evidence of seeded fault testing. Similarly, the ADS-79 Handbook provides guidance on seeded fault testing. It is notable that AC 29-2C MG 15 provides less than a paragraph of text as guidance for seeded fault testing, whereas ADS-79, section 5.9, appendix G, incorporates several pages of guidance on this topic. To fully communicate the benefits of seeded fault testing, the U.S. Army recommends robust, detailed documentation regarding what is necessary and expected for seeded fault testing. ADS-79B, section 5.9 and appendices, currently incorporate much of this detail, which will be expanded in future revisions of the handbook. The degree of information disclosure in both the ADS and AC increases the magnitude of understanding for those seeking methods to obtain credit validation of HUMS and fully realize the benefits of seeded fault testing. The following discussion briefly addresses the similarities and shortcomings of ADS-79 and AC 29-2C MG 15 to highlight key strengths and weaknesses of the two so as to promote collaboration toward maturing both documents in a similar direction.

AC 29-2C MG 15 paragraph g(3)(i) advises using direct evidence for validating HUMS. In addition, AC 29-2C MG 15, paragraph g(3)(i)(A), clarifies direct evidence as having application to tasks classified as “Hazardous/Severe Major,” such as vibration checks on high-energy rotating equipment, fatigue life counting, or going “on condition” for flight critical assemblies. However, nothing advises about applying HUMS and associated CBM tasks based on an RCM analysis.

The stated goal of using seeded fault testing to validate CBM using HUMS is established during the RCM process. Without the RCM process, seeded fault testing is relegated to protracted testing without focusing on the desired end state, wasting both time and money. RCM is the initial focal point for applying any HUMS on an aircraft to accomplish CBM. RCM is referenced several times in ADS-79 as the initial decision point on whether or not to use seeded fault testing to validate CBM with HUMS. RCM analysis provides a basis for developing requirements for CBM to resolve a perceived maintenance issue on an aircraft.

As shown in ADS-79, figure 3 [4], RCM is normally accomplished before visiting the Failure Mode, Effects, and Critical Analysis and FHA on the component of interest and before applying CBM as a candidate solution for maintenance issues. Though the AC 29-2C MG 15 certification process in paragraph e(3) advises performing an FHA, there is no language in the AC tying this into the seeded fault validation methodology. Therefore, it is recommended that AC 29-2C MG 15 address RCM under paragraph g(3) for validation methodology to strengthen the case for choosing, or not choosing, seeded fault testing as a validation methodology.

ADS-79 section 5.9 and the appendices includes steps for carrying out the seeded fault process, such as determining parts to use and faults to seed, processing airworthiness approval, and updating the maintenance task activities. Each section is covered and outlines what is expected from both the U.S. Army platform manager and the manufacturer.

Furthermore, ADS-79 addresses all applications of component and task criticality when pursuing seeded fault testing. When using AC 29-2C MG 15, the guidelines in paragraph f(1)(i)(A) advise: “Systems in the Catastrophic criticality category are not addressed in AC 29-2C MG 15.” In this area, ADS-79 and AC 29-2C MG 15 differ in regard to both hardware and software. All categories of component criticality play an integral part in the planning for seeded fault testing as a validation methodology. Of importance, because a failure in either the MRSP or TRDS hanger bearings would result in a catastrophic failure condition classification and be hazardous to the aircraft occupants, the seeded fault testing for both components was required by the U.S. Army to provide direct evidence to validate any credit used to maintain these components. Maintenance credit validation includes evidence of effectiveness for the developed algorithms, acceptance limits, trend setting data, tests, and the demonstration methods used.

8. CONCLUSIONS

Further research, documentation, example methodologies, and experience need to be accrued to achieve the full benefits of both extending component service time on wing and Condition Based Maintenance (CBM) using seeded fault testing with a Health Usage Monitoring System (HUMS). This holds true not only for the military but also for civilian rotorcraft. It was the intent of this report to provide useful military rotorcraft examples of applying seeded fault testing with HUMS to enable the Federal Aviation Administration (FAA) to provide practical implementation methods requested by industry to meet HUMS requirements for maintenance credits.

Though the main rotor swashplate bearing seeded fault testing is not complete, the methodology and reference information to develop a validation process are provided. With respect to the tail rotor driveshaft hanger bearing example, the investment into seeded fault testing for HUMS led to a maintenance credit achievement via both HUMS and endurance testing.

Seeded fault testing has proven to the U.S. Army to be an important and integral part of CBM and HUMS research. The utmost care should be taken to perform the testing in a manner that closely resembles real world conditions and flight environments to enable a robust validation process for directly correlating HUMS Condition Indicator (CI) and Health Indicator (HI) applications to the aircraft. Realistically, this process will involve both seeded fault test stands and aircraft.

Prior to testing, every aspect of the seeded fault test should be carefully outlined and detailed, commencing with a reliability-centered maintenance analysis incorporating the key elements of the checklist example provided in the “Example HUMS Credit Validation Plan” found in section 2.6.2. Everything should be accomplished while being mindful of the time, costs, and intended goal of the program.

Once testing is complete, the data must be analyzed by an equivalent, or improved, engineering rigor used to establish original maintenance on legacy rotorcraft for pursuing maintenance modification/replacement methods. In addition, post-test direct evidence must continue to be the norm for confirming CI/HI on critical components. This information will be used to develop decisions for both airworthiness and continued airworthiness. As such, confidence and reliability continue to play a key role in analyzing data, developing statistically significant sample sizes, and establishing a substantiated basis for moving away from a legacy aircraft maintenance practice.

The seeded fault test details and processes are outlined in this paper and in Aeronautical Design Standard (ADS)-79 [4]. It is the U.S. Army’s belief that the information in this report can greatly enhance the FAA’s guidance by incorporating aspects of this report and ADS-79 into Advisory Circular 29-2C Miscellaneous Guidance 15 [31].

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APPENDIX A—DEFINITIONS

This appendix contains detailed definitions of terms used throughout the report.

Airworthiness Release (AWR)–A U.S. Army technical document that provides authorization, operating instructions, and limitations necessary for safe flight of an aircraft system, subsystem, or allied equipment.

Baseline Risk–The acceptable risk in production, operations, and maintenance procedures reflected in frozen planning, the Operator's Manuals, and the Maintenance Manuals for that aircraft. Maintenance procedures include all required condition inspections with intervals, retirement times, and time between overhauls.

Condition Based Maintenance (CBM)–The application and integration of appropriate processes, technologies, and knowledge-based capabilities to improve the reliability and maintenance effectiveness of U.S. Army aircraft systems and components. Uses a systems engineering approach to collect data, enable analysis, and support the decision-making processes for system acquisition, sustainment, and operations.

Critical Safety Item (CSI)–Any part, assembly, or installation containing a critical characteristic whose failure, malfunction, or absence could cause loss of or serious damage to the aircraft and/or serious injury or death to the occupants.

Critical Characteristic–Any feature of a CSI—such as dimension; finish; material or assembly; manufacturing or inspection process; installation; operation,; field maintenance; or depot overhaul requirement—which, if nonconforming, missing, or degraded, could cause the failure or malfunction of the CSI.

CBM Maintenance Credit–The approval of any change to the maintenance specified for a specific end item or component, such as an extension or reduction in inspection intervals or Component Retirement Time (CRT) established for the baseline system prior to the incorporation of CBM as the approved maintenance approach. For example, a legacy aircraft with a 2000-hour CRT for a drive system component can establish a change to the CRT for an installed component for which CBM Condition Indicator values remain below specified limits and the unit remains installed on a monitored aircraft. Often, CBM credits may be authorized through an AWR.

CBM Maintenance Debit–The approval of any unfavorable change, from the perspective of the maintainer, to the maintenance specified for a specific end item or component. An example of such would be an increase in inspections or reduction in CRT established for the baseline system that is based on the incorporation of CBM as the approved maintenance approach. For example, a legacy aircraft with a 2000-hour CRT for a drive system component may mandate a decreased CRT for an installed component for which CBM health indicator values go above specified limits and the component is removed from the monitored aircraft. CBM debits are mandated through a Safety of Flight/Aviation Safety Action Message or AWR restriction/limitation.

Confidence Level–The probability that a confidence interval contains the true value of a population parameter of interest. When not otherwise specified in this document, the confidence level shall be assumed to equal 0.9 (or 90%).

Condition Indicator (CI)–A measure of detectable phenomena derived from sensors that show a change in physical properties related to a specific failure mode or fault.

Data Integrity–Data integrity refers to the provisions taken to ensure that the data are unchanged (not missing or corrupted) from when it was initially acquired by the CBM system. Data integrity ensures that data meet a predefined set of rules that are consistent and accurate.

False Negative–A fault is not indicated by the digital source collector but found to exist by inspection.

False Positive–A fault is indicated by the digital source collector but not found to exist by inspection.

Health Indicator–An indicator for needed maintenance action resulting from the combination of one or more CI values.

Health Usage Monitoring System–Equipment, techniques, or procedures by which selected incipient failure or degradation can be determined.

L10 Life–Life of an anti-friction bearing that is the minimum expected life, in hours, of 90% of a group of bearings that are operated at a given speed, temperature range, and loading with the applicable lubricant.

Reliability–The calculated statistical probability that a functional unit will perform its required function for a specified interval under stated conditions.

True Negative–A fault is not indicated by the digital source collector nor found to exist by inspection.

True Positive–A fault is indicated by the digital source collector and found to exist by inspection.

Validation–The process of evaluating a system or software component during, or at the end of, the development process to determine whether it satisfies specified requirements.

Verification–Confirms that a system element meets design-to or build-to specifications. Throughout the system's life cycle, design solutions at all levels of the physical architecture are verified through a cost-effective combination of analysis, examination, demonstration, and testing, all of which can be aided by modeling and simulation.

APPENDIX B—EXAMPLE CALCULATION FOR ESTIMATING RATE OF RETURNS FOR RED-CODED TEARDOWN ANALYSIS COMPONENTS

The following discussion provides an estimate of the rate of incoming main rotor swashplate (MRSP) bearing, Red-coded components. The calculations estimate the rate of gathering Red-coded MRSP bearings, confirmed via teardown analyses (TDAs), due to one Condition Indicator (CI)/Health Indicator (HI).

To date, fleet MRSP bearings provided 14 TDAs from monitored aircraft. Three of the TDAs were rated Red, indicating they required mandatory maintenance. Seven TDAs were rated Yellow, indicating operation within specified limits but with elevated vibration and optional maintenance able to be scheduled to avoid a Red hardware condition. Four TDAs were rated Green for continued operation without elevated or increasing vibration. The four Green data points may be used for this plan to verify the algorithms' abilities to correctly monitor unfaulted conditions with confirmation of hardware condition occurring at normal depot teardown or during special inspection. The Yellow readings may be used to adjust the CI/HI thresholds and trend degrading hardware. The Red readings are used to validate the CI/HI and sought after maintenance credits. The Red readings are the most important of the three condition codes because Red is the reading developed for mandating that a part be removed immediately for maintenance, whereas all other conditions were developed for optional maintenance.

Twenty-two confirmed Red faulted components and 22 Yellow/Green faulted components are required to validate CI/HI for each failure mode—in this case, thermal runaway and spalling. With the three Red confirmed data readings collected from spalled MRSP bearing components, this leaves 19 more to obtain for the spalling failure mode, provided there are no incorrect classifications of faulted and unfaulted components. Among those 19, the plan would call for a minimum of 10 to come from testing to be conducted over the next two years at USC. In accordance with a statistical methodology discussed in ADS-79, if an incorrect classification is made by the Health Usage Monitoring System during data collection, then the number required to obtain 90% reliability and 90% confidence increases to 38 for the spalled failure mode.

Since 10 MRSP spalled bearings are required from seeded fault testing, 12 will be required from the field. From the Department of the Army (DA) Form 2410 database, a rate of Red-coded returns for MRSPs may be constructed, assuming an average annual turn-in rate for MRSPs with fault codes associated with bearings. The DA Form 2410 data in table 2 denotes 93 bearings turned in for bearing-associated faults. The table 2 data were collected over 29.5 months, from January 1, 2009–June 19, 2011. Therefore, MRSPs were returned for bearing-associated faults at the rate of 93 bearings/29.5 months = 3 bearings per month. This is equivalent to a rate of 36 bearings per year for MRSP returns across the entire fleet. The equation for MRSP returns for bearing fault codes is,

$$Return\ Rate = \alpha = \frac{Documented\ DA\ Form\ 2410\ returns\ for\ Bearing\ Fault\ codes}{time} \qquad [B.1]$$

If 98% of an aircraft fleet are equipped with Modern Signal Processing Units (MSPUs), then approximately 98% of the 36 MRSPs turned in per year would come from monitored aircraft,

$$MSPU\% = \delta = \frac{Number\ of\ monitored\ aircraft}{Number\ of\ aircraft\ in\ the\ fleet} \quad [B.2]$$

Therefore, (0.98 * 36) = 35 MRSPs per year are estimated to be returned for bearing-associated fault codes and have monitored data associated with them,

$$\alpha\ X\ \delta = MRSPs\ per\ year\ estimated\ to\ be\ returned\ for\ bearing\ faults\ with\ data \quad [B.3]$$

Using previous TDA data as a predictor of future TDAs, the last year's rate of Red-coded TDAs out of all condition-based maintenance (CBM) Quality Deficiency Reports (QDRs) is used to determine future return rates. For this example, there were 14 TDAs from 2010–2011, three of which were coded Red. This is a 14% return rate for Red-coded TDAs from previous fleet monitoring practices,

$$\%\ of\ Reds\ from\ all\ CBM\ QDRs = \beta = \frac{previous\ Red\ TDAs\ in\ a\ year}{all\ previous\ TDAs\ in\ a\ year} \quad [B.4]$$

The 35 per year returned for bearing fault codes is further reduced by 14%, β, making the total estimated MRSP to be returned with monitored data five per year. Therefore, five Red-coded TDAs per year are expected to be MRSP CBM QDRs received from the field,

$$\beta * (\alpha * \delta) = MRSPs\ per\ year\ estimated\ to\ be\ returned\ for\ bearing\ faults \quad [B.5]$$

In this case, it is estimated that at five Red-coded TDAs per year from CBM QDRs, it would require (12 field QDRs needed/5 received in one year) = 2.5 years to receive the necessary data for validation of a CI.

If all the other failure modes are not being monitored by a single CI, then the case would need to be modified. The MSPU system may be capable of detecting multiple failure modes, but if a CI can only monitor one, the calculations must continue. Since the rate of return for only one CI is needed, it would be necessary to eliminate all of the incoming QDRs pulled for failure modes not monitored by that CI. In the case of the MRSP, there are two monitored failure modes: spalling and overheating. For the five Reds/year estimated to be returned from monitored aircraft, one out of the two failure modes would need to be removed since a CI did not monitor all failure modes, leaving only two to three Red-coded TDAs per year,

$$Failure\ Mode\ reduction = \gamma = \frac{1}{all\ monitored\ failure\ modes} \quad [B.6]$$

Because some failure modes occur more often than others, an alternate way of calculating γ would be to calculate the percentage of that failure mode out of the QDR created. This can be done by looking at the previous CBM TDA and creating a ratio of the TDA due to the failure mode being detected by the CI/HI,

$$\gamma = \frac{Number\ of\ TDAs\ due\ to\ particular\ Failure\ Mode}{All\ previous\ TDAs} \quad [B.7]$$

Or by looking at all QDRs, inside and outside of CBM, and creating a ratio of QDR due to the failure mode,

$$\gamma = \frac{Number\ of\ QDRs\ due\ to\ Failure\ Mode}{All\ QDRs} \qquad [B.8]$$

Therefore,

$$Rate\ of\ Red\ Returns\ per\ year\ for\ a\ single\ CI = [(\alpha * \delta) * \beta] * \gamma \qquad [B.9]$$

In this case, it is estimated that at two Red-coded TDAs per year from CBM QDRs, it would require (12 field QDRs needed/2 received in a year) = 6 years to receive the necessary data for validation of a CI.

APPENDIX C—AVIATION ENGINEERING DIRECTORATE SUBSTANTIATION FOR ON CONDITION TAIL ROTOR DRIVE SHAFT HANGER BEARINGS

Table C-1 shows an acceptable grease life calculation for the Tail Rotor Drive Shaft (TRDS) Hanger Bearing with 90% reliability and 90% confidence.

Table C-1. Grease Life Calculation for TRDS Hanger Bearing

Hanger Bearing Equivalent Operating Hours					
Test Temp Level	at ~200° F	at 295° F	at 315° F		
Acceleration Factor	1.00	5.64	9.08		
Weibull β	1.1				
Bearing	Time (hrs)	Time (hrs)	Time (hrs)	Total Equiv Time	t^{β}
Bearing 1, S/N ARL-008:		1,270	325	10,116.4	25,440.6
Bearing 2, S/N ARL-009		1,270	325	10,116.4	25,440.6
Bearing 3, S/N 01328		1,270	325	10,116.4	25,440.6
Bearing 4, S/N 01320	1,108	370	325	6,147.1	14,707.4
Bearing 5, S/N 01321		370	325	5,039.1	11,819.2
Bearing 6, S/N ARL-007		1,270	325	10,116.4	25,440.6
Bearing 7, S/N 01345		1,270	325	10,116.4	25,440.6
Bearing 8, S/N 01311	1,108	1,270	325	11,224.4	28,521.8
Bearing 9, S/N ARL 006		900		5,077.3	11,917.7
Bearing 10, S/N ARL 010		900		5,077.3	11,917.7
				83,146.9	206,086.7

Reliability	90%	90%
Confidence Level	90%	95%
Weibull η	31744.4	24990.2
B10 Life	4103.9	3230.7

Desired B10 Life	3250
Confidence Level at 3250	94.9012%

Continue Testing Bearings 4 & 8	
Additional Equiv Time, 4	250
Additional Equiv Time, 8	250
New t^{β}	207,445.5
New Confidence Level at 325	95.0002%