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A PROCESS TO DIGITALLY MAP HELICOPTER MAIN ROTOR BLADES IN SUPPORT OF CONDITION BASED ACQUISITION AND SUSTAINMENT ACTIVITY

September 2021

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The Black Hawk utility helicopter is a valuable warfighting asset in the Army aviation fleet. The helicopter also has a substantial sustainment and maintenance cost. One particular subsystem of the helicopter is the main rotor blade, which is a critical component for flight and has a substantial procurement and sustainment cost. For the purpose of this research, we examine current main rotor blade inspection methods, investigate advanced inspection technologies, and produce a concept of integration. Digital imaging is also introduced to show how an automated method for inspection produces a return on investment that is worth exploring. The recommendations of using new technologies for the Black Hawk main rotor blades has the potential to not only prevent unnecessary overhaul and repair costs of a rotor blade but also to reduce the schedule associated with sustainment and the logistics footprint. Overall, the recommendations shown in this research offer the Army an opportunity to modernize sustainment practices and reduce maintenance burdens. These same recommended improvements are not limited to the Black Hawk fleet but may be considered for application across the Army sustainment enterprise to increase materiel reliability and improve warfighting capabilities.

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ABSTRACT

The Black Hawk utility helicopter is a valuable warfighting asset in the Army aviation fleet. The helicopter also has a substantial sustainment and maintenance cost. One particular subsystem of the helicopter is the main rotor blade, which is a critical component for flight and has a substantial procurement and sustainment cost. For the purpose of this research, we examine current main rotor blade inspection methods, investigate advanced inspection technologies, and produce a concept of integration. Digital imaging is also introduced to show how an automated method for inspection produces a return on investment that is worth exploring. The recommendations of using new technologies for the Black Hawk main rotor blades has the potential to not only prevent unnecessary overhaul and repair costs of a rotor blade but also to reduce the schedule associated with sustainment and the logistics footprint. Overall, the recommendations shown in this research offer the Army an opportunity to modernize sustainment practices and reduce maintenance burdens. These same recommended improvements are not limited to the Black Hawk fleet but may be considered for application across the Army sustainment enterprise to increase materiel reliability and improve warfighting capabilities.

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	Army Commands
AFC	U.S. Army Futures Command
AGL	Above Ground Level
ALC	Aviation Logistics Center
AMAM	Aviation Maintenance Action Message
AMC	U.S. Army Materiel Command
AMCOM	Aviation and Missile Command
AMD	Average Monthly Demand
AMS	Army Modernization Strategy
AR	Army Regulation
ASA(ALT)	Assistant Secretary of the Army (Acquisition, Logistics and Technology
ASAM	Aviation Safety Action Message
ASTM	American Society for Testing and Materials
ATM	Aircrew Training Manual
AVN	Aviation
AWR	Airworthiness Release
BCAC	Business Capability Acquisition Cycle
BO	Back Order
C4ISR	Command, Control, Communications, Computers (C4) Intelligence, Surveillance and Reconnaissance (ISR)
CAD	Computer-Aided Design
COAs	Courses of Actions
COTS	Commercial off the Shelf
DCMA	Defense Contract Management Agency
DOD	Department of Defense
DFARS	Defense Federal Acquisition Regulation Supplement
DMWR	Depot Maintenance Work Requirement
EIR	Engineering Investigation Report
EIS	Enterprise Information Systems

FAR	Federal Acquisition Regulations
FARA	Future Attack and Reconnaissance Aircraft
FMECA	Failure Mode, Effects and Critical Analysis
FLRAA	Future Long-Range Assault Aircraft
FMC	Fully Mission Capable
FRACAS	Failure Reporting, Analysis, and Corrective Action System
FVL	Future Vertical Lift
FY	Fiscal Year
GFE	Government Furnished Equipment
GFI	Government Furnished Information
GOTS	Government off the Shelf
IDIQ	Indefinite Delivery/Indefinite Quantity
IP	Intellectual Property
IRT	Infrared Thermography
IVHMS	Integrated Vehicle Health Management System
JDRS	Joint Deficiency Reporting System
KIAS	Knots of Indicated Air Speed
LDAC	Logistics Data Analysis Center
LMP	Logistics Modernization Program
LOGSA	Logistics Support Activity
MA	Maintenance Actions
MAM	Maintenance Advisory Message
MEL	Maintenance Expenditure Limit
MC	Mission Capable
MCDS	Maintenance Consolidated Database System
M&O	Maintenance and Operations
MRB	Main Rotor Blade
MTBF	Mean Time Between Failure
MTBR	Mean Time Between Removal
MTBRRDR	Mean Time Between Removals Requiring Depot Return
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization

NDT	Non-Destructive Test
NICP	National Inventory Control Point
OEM	Original Equipment Manufacturer
OPR	Office of Primary Responsibility
PDF	Portable Document Format
PDREP	Product Data Reporting and Evaluation Program
PEP	Propellants, Explosives, and Pyrotechnics
PEO	Program Executive Officer
PMC	Partially Mission Capable
PMD	Preventative Maintenance Daily
PMI	Phase Maintenance Inspection
PMO	Project Management Office
PMS	Preventative Maintenance Service
PQDR	Product Quality Deficiency Report
PRON	Purchase Request Order Number
QA	Quality Assurance
QC	Quality Control
RAM	Reliability, Availability, and Maintainability
RIMFIRE	Reliability Improvement thru Failure Identification and Reporting
ROI	Return on Investment
SOF	Safety of Flight
SOH	Supply on Hand
S&R	Strip and Rebuild
sUAS	Small Unmanned Aircraft System
TAMMS	The Army Maintenance Management System
TAMMS-A	The Army Maintenance Management System - Aviation
TRADOC	U.S. Army Training and Doctrine Command
UH	Utility Helicopter
WBS	Work Breakdown Schedule

EXECUTIVE SUMMARY

As Department of Defense and Army directives push for modernization of defense systems and increased reliability of weapon systems, it is imperative that critical warfighting systems and components are adequately inspected and examined in order to meet all directives. The Black Hawk helicopter main rotor blade is one of those critical components within the Army fleet of aircraft. Due to the stresses induced to provide lift to an aircraft, the rotor blade is designed as a complex composite system that contains multiple layers of material. This report breaks down the examination and research conducted on current sustainment activities into the following sections: background, research methodology, results, and closeout. A brief summary of each section is provided below.

The background section of this report identifies the overall processes that occur during the sustainment phase of the Black Hawk main rotor blade life cycle in response to Army directives with the intent to maintain an operationally capable fleet. The details of the background section cover several aspects ranging from time change requirements for overhauls to reporting methods, aviation messages, and enduring and present concerns plaguing Black Hawk rotor blades. This section is intended to provide a baseline understanding of the requirements driving the activities conducted to ensure a main rotor blade is reliable and mission ready. This section concludes with the identification of concerns that are noted within the Black Hawk community via aviation messages. These aviation messages are generated in order to direct the Black Hawk community to address suspect or confirmed rotor blade issues. Thus, the current methods of ensuring rotor blade reliability such as inspections, repairs, or overhauls are less than efficient in meeting the needs of the warfighter.

Following the background section, the research methodology section examines the activities occurring within the sustainment processes to meet the quality and reliability requirements of Army directives for aircraft components. Current inspection processes are identified in this section along with non-destructive inspection methods. Current test

methods can be aged in decades instead of years and can be very subjective or non-conclusive.

Newer inspection technologies examined are shearography and thermography. Both of these technologies are similar such that they are capable of providing digital imaging of composite structures, so defects can be easily identified at a very small level. The combined hardware and software used in shearography and thermography is capable of developing digital images, or digital maps, of components, which can be valuable tools for detecting potential failures of a critical flight component. Current and past industry uses of these technologies are provided as examples to show the potential for improved inspection methods to be introduced into the Black Hawk rotor blade inspection processes. The investigation into new inspection technologies leads this report into the results section to investigate the potential for improving sustainment operations of Black Hawk main rotor blades with improved technology.

The results section of this document outlines a description of comparative image processing along with an abstract on how digital images are computationally compared. Since shearography and thermography result in improved data analytic tools and can provide digital maps of a composite structure, they are ideal candidates for proposing a concept of induction into the inspection process of the main rotor blade. Examples of potential improvements are captured in the results section of this document, which present the opportunity for substantial cost and time savings coupled with the chance to prevent failures with early detection of defects. In addition to the proposed integration of a new inspection method, the current process map is identified in a flow diagram that shows how many times a person is required to make a decision on the reliability of a rotor blade. The intent of this diagram is to show how many times human error can affect the decision matrix of a main rotor blade.

In summation, the research and information gathered lead to the recommendations of adopting new inspection technologies to create baseline digital images of each rotor blade, digital image histories, and computer-aided systems for analyzing component maps. These suggestions would standardize the data collection methods and evaluate deviation in the digital repository while minimizing human subjectivity. Digital component mapping, computerized analysis, and integrated data repository would put the U.S. Army on course toward full digital integration and directed modernization efforts.

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I. INTRODUCTION

A. PURPOSE

The U.S. Army faces a monumental task of maintaining the reliability of equipment to support combat readiness. The 21st century adversaries are far more advanced and pose even more of a threat than the 20th century Cold-War era. We have witnessed their capability through cyber, proxy wars, and regional alliances by way of aid.

Advanced manufacturing methods and materials, fused with digital engineering, in theory results in a revolution of how the Army designs, delivers, produces, and sustains, and improves materiel capability. As mentioned in the above statement, it will provide the Army a means to modernize weapons systems and maintain technological advantage over adversaries.

According to a 2019 Army directive titled *Enabling Readiness and Modernization Through Advanced Manufacturing*,

> Advanced manufacturing refers to activities that depend on the use and coordination of information, automation, computation, software, sensing and networking, and/or make use of cutting-edge materials and emerging capabilities enabled by the physical and biological sciences. It encompasses new ways to manufacture existing products and the manufacturing of new products resulting from advances in technology. (Department of the Army [DA], 2019a, p. 1)

The memo also notates some common advanced manufacturing methods and materials that "includes, but is not limited to, additive manufacturing (also known as three-dimensional [3D] printing), artificial intelligence, robotics, and advanced composite materials" (DA, 2019a, p. 1). In general, the intention of the memo is to point out that the fusion of traditional manufacturing processes with modern manufacturing methods and materials creates a disruptive opportunity that will improve the way the Army develops, produces, and continues materiel capabilities.

There are key areas that advanced manufacturing, along with digital enterprise systems, improve. A few of those areas are:

- innovation
- modernization
- performance
- reliability
- sustainment
- obsolescence

Modern equipment requires expediency to meet combat readiness, but it also must outperform and extend system reliability. These advanced methods will decrease time-to-market, ensuring warfighters obtain critical capabilities as needed. Reduction on the Army's logistics footprint can also be achieved through minimizing risk of obsolete parts and diminishing supply.

The overall objective will require organizations across the Army to adopt advanced manufacturing techniques. The 2019 Army directive identifies these organizations to include "requirements, research and development, acquisition, sustainment, and contracting activities" to provide superior capabilities and overmatching our near-peer adversaries (DA, 2019a, p. 2).

This report will focus on a critical component of the Army's Black Hawk helicopter. It will also detail the current life cycle processes to better understand whether the Army is able to adjust to meet these demands to stay ahead. The recommendations set forth, in the conclusion, will address inefficiencies that are detailed within this research.

This research shall evaluate the Black Hawk main rotor blade (MRB) quality control mechanisms, some manufacturing and sustainment processes, reported component deficiencies and enterprise efforts to mitigate identified risks. Figure 1 is an adapted image from an Army Technical Manual that shows an overall outline of the UH-60 Black Hawk aircraft. Figure 2 is an extract from an automated logistics critical item database called reliability improvement thru failure identification and reporting (RIMFIRE), which shows a Black Hawk rotor blade. This document will articulate the benefits of digitally mapping MRBs throughout the component life cycle and the associated inspection technologies that could support digital mapping. The following are the research questions:

- Could digitally mapping MRBs provide a decision-making template to assist in evaluating component integrity to design specification?
- Are the benefits of digitally mapping MRBs throughout the component life cycle quantifiable?
- Do past and present MRB inspection methods and component documentation procedures still provide the best sustainment for the Army as we advance further into a growing digital environment and prepare for future conflicts?

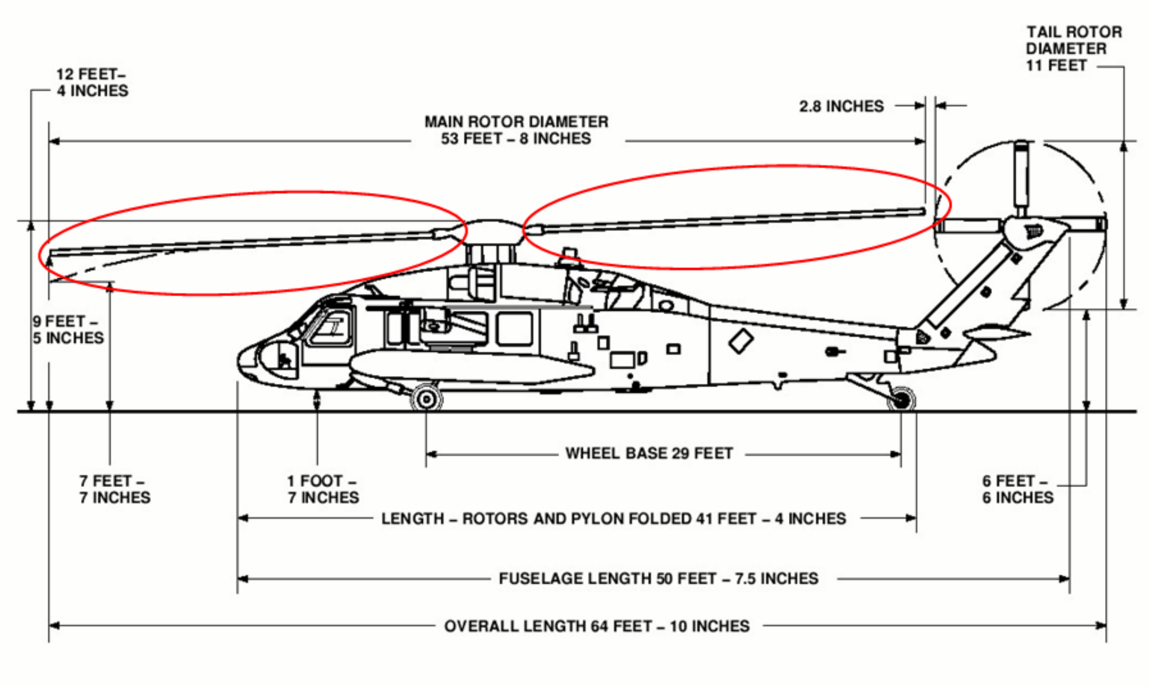

Figure 1. UH-60 Black Hawk Main Rotor Blades. Adapted from U.S. Army Technical Manual TM 1-1520-237-10 (1996).

Figure 2. Black Hawk MRB. Source: RIMFIRE (2018).

B. TERMINOLOGY

Digital mapping refers to the practice of gaining a present condition depiction of a component to identify suspect flaws in material or to enable a digital comparison. For the purpose of this research, the terms digital map and digital image will be used interchangeably. Some new technologies will be explored in order to evaluate the feasibility in application for a Black Hawk MRB. Every alternative will have inherited weakness either through scan time, floor space, resourcing, and/or costs. Some new technologies that offer some promising improvements will be identified and analyzed through this research.

C. SCOPE OF CONCERNS

The main rotor system and its dynamic components are a most vital part of any helicopter. Helicopter main rotor systems rely on rotary wings and complex control systems to generate sufficient aerodynamic force to achieve flight. A helicopter rotary wing is most often referred to as a MRB. The MRB is a key component of the helicopter main rotor system.

The main rotor blades on a helicopter may be compared to tires on a car, each are subject to many factors that affect their longevity of use. Similar to periodic tire servicing; MRBs require routine inspections, repair or replacement when necessary, and proper sustainment planning to schedule necessary resourcing. Tire failures often result in automobiles easing to the shoulder of the road; unfortunately, when a MRB of an aircraft fails the effects can be catastrophic—particularly if the aircraft is in a critical mode of flight or thousands of feet above ground. Early fault detection is critical to safe operation and prolonged component life. Environmental conditions coupled with the dynamic forces required for flight place variable stresses on a MRB. Additional factors impacting MRB sustainment fall into the following categories:

1. Performance

When it comes to helicopters, engines alone do not determine how well the aircraft performs. Rather, it comes down to how well the rotor blades handle power input and the amount of aerodynamic force required to produce lift and thrust. Aircraft weight, airspeed, and density altitude are three major environmental factors influencing MRB performance. Figure 3 is an example of a height velocity (H/V) diagram. The risk of unfavorable outcomes increases during loss of lift events when a helicopter remains for prolonged periods within the avoid region depicted on the performance chart. The engines and rotor system may not be capable of overcoming the effects of gravity and adverse environmental conditions should a loss of MRB lift occur.

Helicopters operate routinely within the avoid area of the performance chart. Varieties of missions require such operation; routine observance of transient controlled flight occurs during takeoff, landing, and hovering events. Optimal MRB design with reliable and uncompromised material integrity help ensure adequately driven rotor systems perform safely through their intended flight regimes.

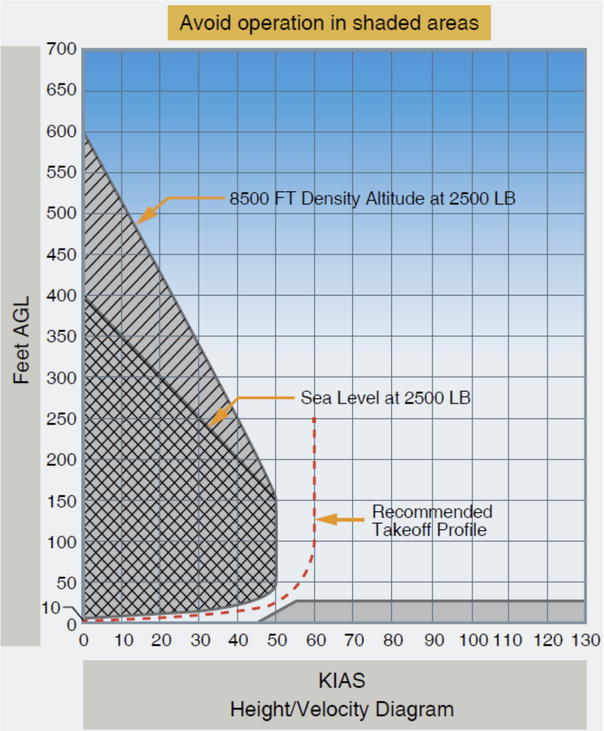

Figure 3. Sample Height/Velocity Diagram. Source: Flight Literacy, https://flightliteracy.com/helicopter-performance-charts-part-one/, n.d.).

2. Product Assurance

MRBs are subjected to reliability, availability, and maintainability (RAM) policy set forth from the Department of the Army, Army Regulation (AR) 702-19. The regulation identifies requirements for RAM associated with combat or mission essential items for military use. More specifically, AR 702-19 states:

> This regulation sets forth policies for planning and managing Army materiel systems' reliability, availability, and maintainability (RAM) during development, procurement, deployment, and sustainment. It applies to all combat or mission essential developmental, non-developmental, commercial items adapted for military use, and product improved hardware and software systems. Materiel systems also include, but are not limited to, stand-alone or embedded automatic data processing equipment hardware and software; support and ancillary equipment comprising the total materiel system; and multi-Service materiel systems when the Army is lead Service. (p. 1)

Black Hawk MRBs are costly, critical safety item components and inherently fall within the oversight boundaries of RAM policy. The aviation program executive office is responsible for ensuring RAM analysis occurs throughout the MRB life cycle. RAM analysis provides information to evaluate product assurance by identifying trends in sustainment activities including type of component repairs, rates of replacement and component failure reports—helping formally address operational trends and mitigate above baseline risk.

3. Obsolescence

According to a 2017 Department of Defense (DOD) acquisition note regarding obsolescence, it is observed as the "lack of availability of an item or raw material resulting from statutory and process changes, as well as new designs. Obsolescence deals with the process or condition by which a piece of equipment becomes no longer useful, or a form and function no longer is currently available for production or repair. Implementation of new technology causes older technology to become less supportable because of the diminished availability of parts and suppliers" (AcqNotes, 2017).

As the Black Hawk enduring fleet ages, so does the supply chain and the manufacturing that goes with it. Adequate inventory must be purchased to ensure the Army has an ample supply of MRBs to mitigate obsolescence concerns. No matter if the United States is at peace or actively involved in war, the reliability of supply is a necessity during the procurement process.

4. Innovation

Innovation can be characterized as a new idea or method. When it comes to helicopter blades, it could mean a new design that improves cost, reliability, or performance. However, innovation is not limited to brand new designs. Innovation can be seen as new methods of production, revised processes, or inspection methods. In this document, innovation will be approached from the perspective of improving sustainment activities by means of inspection. Using a new innovative approach for MRB inspections, opportunities for cost savings, time savings, and improved inventory reliability will be explored to identify a return on investment (ROI).

5. Army Modernization

The 2019 *Army Modernization Strategy* prescribes how the future Army will shape out in 2035. This document outlines a path forward for the Army to transition into the Army of tomorrow. One particular section of the modernization strategy specifically addresses the overarching goal of Army aircraft and component improvement such as "platforms and technologies increase the maneuverability, endurance, lethality, and survivability of Army aircraft—increasing their operational reach and effectiveness against near-peer competitors" (DA, 2019a, p. 6). As the Department of Army looks to capitalize on modernizing existing products and processes, it only makes sense to examine the numerous, relatively expensive and critical main rotor blades used on the Black Hawk helicopter.

D. PAST, PRESENT, AND FUTURE

MRBs supporting current Army aviation aircraft for combat readiness went through decades of research and development. Many of the methods and processes of ensuring reliability and performance of Black Hawk MRBs date back to the original introduction of the helicopter in the late 1970s and early 1980s. It becomes more apparent each year that established methods of inspection are becoming outdated, and some of the inspections may be improved utilizing new technologies. As will be examined in this research, current sustainment costs associated with maintaining a mission ready supply inventory of MRBs is becoming increasingly more cost prohibitive. As directed through Department of Army memos and guidance, opportunities to take advantage of technologies to improve readiness and modernize our nation's defenses should be evaluated. The question must be asked, do past and present MRB inspection methods and component documentation procedures still provide the best sustainment for the Army as we advance further into a growing digital environment and prepare for future conflicts?

The following chapter will provide a brief background of the Black Hawk MRB and provide a summary of data collection tools used to analyze fleet readiness. Chapter III will outline the research methodology that was taken to identify existing areas where improvements could be made. Also included are some overall values associated with MRB readiness, current inspection methods, and possible technologies that could be implemented to enhance inspections. Chapter IV will be used to analyze the results of the research conducted on MRB sustainment improvements and the level of impact that could be seen. Digital mapping resulting from the implementation of newer technologies and the associated advancements in efficiencies will also be examined in the same chapter. Chapter V presents conclusions of findings and final recommendations for consideration.

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II. MRB BACKGROUND

As mentioned earlier, the MRBs are a vital component of the helicopter. Modern-day MRBs are no longer made from wood. Modern helicopter rotor blades are made of a mixture of materials. Titanium, carbon fiber, fiber glass, and stainless steel can all be found in the vast array of main rotor blades designs. Some designs are simple, and some are highly complex (James, 2021).

The U.S. Army Black Hawk fleet utilize two different MRB designs. The H-60A/L/V series aircraft utilize a variation of the original MRB delivered on the first Black Hawk, minor design changes included improvements in the blade cuff and tip cap regions of the assembly intended to increase durability. The H-60M series utilize an improved wide chord MRB design adapted from a commercial helicopter—providing greater lift and noise reduction. Our analysis will highlight sustainment challenges with the original MRB and how like challenges remain a concern in ongoing MRB sustainment efforts.

The evolution of material continues as the demands on helicopter vertical lift capability increases. The Army's future vertical lift (FVL) is an ambitious program modernizing the Army's aging aviation fleet. This program is identified in the Army's top six modernization priorities. The seven tenants of FVL are:

- improved maneuverability
- improved range
- improved speed
- improved payload
- improved survivability
- improved reliability
- reducing logistical footprint

No matter the vertical lift platform we are looking at, from future long-range assault aircraft (FLRAA) to future attack and reconnaissance aircraft (FARA), or the present enduring fleet, the MRB is key to supporting Army priorities. As FVL ramps up in development, we still need to ensure that our current platforms remain readily available and capable of withstanding harsh combat conditions. (Congressional Research Service, 2021) Thus, analysis of the Black Hawk MRB is where this research focuses.

As the Black Hawk MRB transitions through its acquisition life cycle, it has been subjected to various sustainment processes. The five major events that impact the usability of the MRB throughout its life cycle are: time change/retirement change, failure mode effects and criticality analysis, quality assurance (QA), product quality deficiency reports, and aviation messages. Each of these events are employed to mitigate or identify defects with the MRB itself. Below are the processes impacting a typical MRB as it transitions through its life cycle.

A. TIME CHANGE / RETIREMENT CHANGE (TC/RC)

According to a Department of the Army pamphlet 738-751, time change (TC) is referred to as “an item that has a fixed operating time between overhauls based on safety margin or design limitations. The item must be replaced with a new or fully serviced item after the specified time” (DA, 2014b, p. 180). Once an MRB reaches its TC, it will then be overhauled at a depot level facility to be returned to service later.

In order to identify the maximum allowable operating time (MAOT) of an aircraft component, Army pamphlet 738-751 describes retirement change (RC) as “an item that has been assigned a safe maximum allowable operating time since new, that the item can safely be operated before it must be removed from service, mutilated, and lost out of Army inventory. This item can be repaired prior to reaching its MAOT, normally RC items will not be overhauled, and must be removed from service when it reaches its MAOT” (DA, 2014b, p. 179).

B. FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS (FMECA)

According to TM 5-698-4: “The FMECA is composed of two separate analyses: the failure mode and effects analysis (FMEA) and the criticality analysis (CA). The FMEA analyzes different failure modes and their effects on the system as a whole while the CA classifies, or prioritizes, their level of importance based on failure rate and severity of the effect of failure. The ranking process of the CA can be accomplished by utilizing existing failure data or by a subjective ranking procedure conducted by a team of people with an understanding of the system” (DA, 2006, p. 4-1).

A company titled Quality-One International lists on their website that “FMECA is a bottom-up (hardware) or top-down (functional) approach to risk assessment. It is inductive, or data-driven, linking elements of a failure chain as follows: effect of failure, failure mode and causes/mechanisms” (Quality-One International, n.d.). It also says:

> The effect of failure duplicates the experience of a user/customer and is then translated into the technical failure description or failure mode. The technical failure description answers the question “why,” introducing causes that result in the failure mode. Each failure mode has a probability assigned and each cause has a failure rate assigned. If data is not available, probability of occurrence is assigned. The probability depends on the failure data source documents utilized in the FMECA. The FMECA is performed prior to any failure occurring. FMECA analyzes risk, which is measured by criticality (the combination of severity and probability), to act and thus provide an opportunity to reduce the possibility of failure. (Quality-One International, n.d.)

For application to the Black Hawk MRB, the FMECA process is typically conducted in the bottom-up approach. The FMECA analysis is based on test results and the identified failures of a blade. The MRB cuff and spar assembly are the most critical interfaces for MRB integrity. The tip cap and skin bond are secondary but are also critical components that can have a major impact on MRB integrity.

It is useful to note that another complimentary method of addressing and mitigating reliability and maintainability issues throughout the entire life cycle of an aviation component is to use a failure reporting, analysis, and corrective action system (FRACAS). The FRACAS was identified as an acquisition requirement in the September 1980 military standard 785 with the later military handbook 2155 detailing the uniform requirements of a FRACAS. Per military handbook 2155 the FRACAS and FMECA are complimentary, yet independent, tools that generate a synergistic effect when they are combined (DOD, 1995, p. 7). The same handbook differentiates the two efforts by identifying FMECA as an "analytically derived identification of the conceivable hardware failure modes of an item and the potential adverse effects of those modes on the system and mission. The FMECA's primary purpose is to influence the system and item design to either eliminate or minimize the occurrences of a hardware failure or the consequences of the failure. The FRACAS represents a 'real world' experience of actual failures and their consequences" (DOD, 1995, p. 7).

C. QUALITY ASSURANCE

The federal acquisition regulation section 46.202-2 identifies the requirements for quality assurance that are leveraged on prime contractors. The original equipment manufacturer (OEM) and associated vendors are responsible for quality assurance of materiel delivered to the United States government. Defense contracting management agency (DCMA) representatives perform surveillance checks during the manufacturing process to ensure configuration compliance with source control documents. (Federal Acquisition Regulation [FAR], 2019) After the MRBs are deemed acceptable by the DCMA, a transfer of hardware can be attained from the manufacturer to government inventory through the DD250 process.

Once the Black Hawk MRBs have transitioned into Army inventory from the OEM, they are subject to Army quality standards prescribed in AR 702-11 *Army Quality Program.* To aid with quality standards, the Army developed a software tool/database known as the Army maintenance management system (TAMMS). The DA PAM 750-8, *The Army Maintenance Management System (TAMMS) User's Manual* states:

> The purpose of the Army Maintenance Management System (TAMMS) is to assist commanders at all levels in managing equipment use and operations, equipment maintenance, and repair operations and to maintain equipment to the Army standard as outlined in Army Regulation (AR) 750–1. It also provides the foundation for materiel condition status reporting

> (MCSR) as outlined in AR 700-138 and controlling equipment as outlined in AR 600-55.
>
> TAMMS is a comprehensive management information system, consisting of automated information components and records, manually maintained components and records, and a central Army database at Logistics Support Activity (LOGSA). This central database is the Maintenance Module of the Logistics Integrated Database and is used by all Army commands.
>
> TAMMS uses a set of time-proven maintenance processes, engineering practices, and industry standards. The TAMMS process and maintenance records enable commanders to manage equipment readiness, availability, and durability, based on the level of resources provided by higher command. Resources include the application of time, trained personnel, tools, test equipment, and funds. (DA, 2005, p. 1)

While TAMMS is used at both field and sustainment level maintenance activities, RIMFIRE is a sustainment level decision support system database, detailing component condition upon initial inspection for repair, overhaul and rebuild. RIMFIRE provides critical component information to material developers and item managers performing national inventory control point sustainment activities.

As this document evaluates new technologies as additive or replacement inspection methods for Black Hawk MRBs, it is assumed that the existing RIMFIRE database will be matured to utilize digital data gathered during the application of new inspection methods. As demand for additional data storage increases, additional servers and/or network attached storage devices may be required to support a centralized digital mapping effort. The adaptation of digital mapping software may help achieve a timelier, automated analysis by comparing digitized records including component images.

D. PRODUCT QUALITY DEFICIENCY REPORTS (PQDR)

AR 702-7-1 states that "the Army will process all PQDRs in accordance with this regulation. The purpose of the PQDR program is to remove defective nonconforming and/or dangerous items from the Army inventory; provide remediation to the unit for defective items; determine the root cause of the defective item to prevent its reoccurrence; and collect failure and nonconformance data for trend analysis to continuously improve system performance. The PQDR program establishes official product quality feedback channels to the designated Army national inventory control point (NICP) responsible for the product design, procurement and distribution of items and materiel identified as defective, and provision of a means for correcting deficiency” (DA, 2020b, p. 1).

For the PEO AVN, the PQDRs are a common tool used to identify deficiencies in the Black Hawk MRBs and monitor progression from identification through disposition. As this research looks at new methods for inspection, it is understood that an inspection may lead to the generation of a PQDR for an MRB or that a PQDR may lead to an inspection based on findings in the field. Either way, a new inspection technology will assist in remedying any suspect failures of a composite MRB.

E. AVIATION MESSAGE SUMMARY/AVIATION MAINTENANCE ACTION MESSAGE (AMAM)

Over the last decade, no fewer than 19 aviation messages have been released involving Black Hawk main rotor blades: 2-safety of flights (SOF), 10-aviation safety action messages (ASAM) and 7-AMAMs. Each of these message types are critical and provide alerts to appropriate stakeholders regarding aviation equipment. These messages also pertain to the Black Hawk MRB and require some form of action, or acknowledgement, once released. The below paragraphs detail the three types of safety messages and the impact they have.

A United States Aviation and Missile Command news article from 2020 titled *Safety of Flight Messages Saves Lives* states,

> SOF messages are high-priority notifications pertaining to any defect or hazardous condition of an Army-fielded system that can cause personal injury, death, or damage to the system. SOF messages can restrict specific performance capabilities, operational limits, or require immediate maintenance actions for a variety of reasons that could include material defect conditions. Depending on the severity of the defect, the entire fleet or a portion of the fleet could be grounded. (Miller, 2020)

SOF messages require an immediate response from the OEM and PEOs to address the findings.

ASAMs “convey aviation or equipment maintenance, technical, or general interest information where a low to medium risk safety condition has been determined per AR

385-10 or an Army approved risk decision matrix. These messages are of a lower priority than a SOF" (DA, 2018, p. 4). "These messages may require accomplishment of a task or tasks and require report of completion or findings" (DA, 2018, p. 4). An ASAM can have three different categories depending on the results of investigative efforts: maintenance mandatory, operational, informational. When specifically associated with aviation, the formal tag for this message is AMAM where the MA is the generic Army message. The descriptions of the three versions of an ASAM are defined per AR 750-6 *Maintenance and Supplies of Equipment - Army Equipment Safety and Maintenance Notification System* as:

> Maintenance Mandatory: directs maintenance actions (MAs) and/or updates technical manuals and may also require compliance reporting and task/ inspection reporting.
>
> Operational: pertains to aircraft or equipment operation, flight or ground procedures, limitations, or operational policy.
>
> Informational: provides status and information of a maintenance, technical, or general nature. (DA, 2018, p. 4)

As a subset of the ASAM, the AMAM specifically drives a maintenance requirement out to the PEOs and OEMs. The AMAMs "convey maintenance, sustainment, logistics supply, technical, operational, or general maintenance, or sustainment interest information that is not related to safety and will not be used to mitigate risk" (DA, 2018, p. 4). AR 750-6 states that the purpose of the AMAM "is to mitigate negative maintenance, logistics, sustainment, or maintenance operational impacts" (DA, 2018, p. 4).

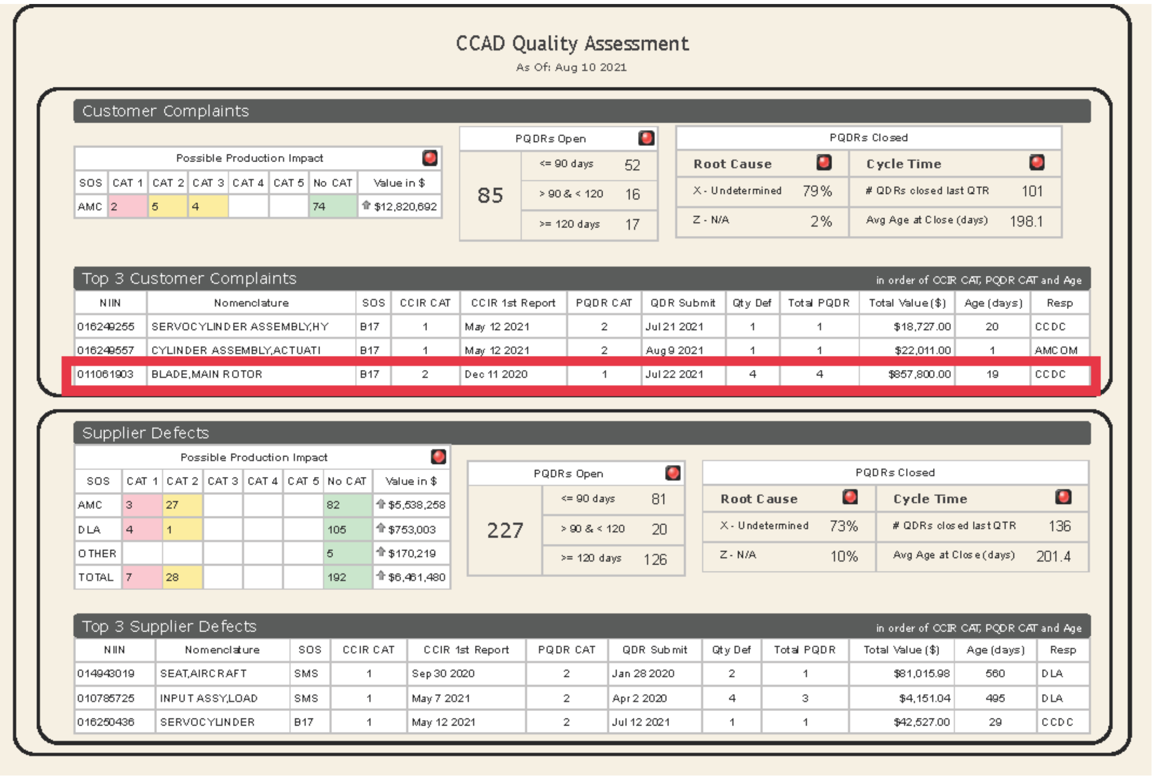
Many of the aviation messages have alerted the aviation stakeholders of issues regarding the MRBs and enforced modified inspection procedures or replacement intervals that are intended to ensure component integrity. Directed changes were implemented to mitigate identified risks or improve material readiness at both field and sustainment level maintenance activities.

F. ENDURING/PRESENT CONCERNS

The aviation messages referenced above address systemic production and environmental use concerns adversely impacting MRB safety and reliability—including the MRB cuff, tip cap, core bond, and weight/balance adjustments. Several of the messages introduce expanded inspection methods and inspection frequencies to mitigate known concerns. The released messages have not resolved all identified concerns, and the fleet continues to struggle with sufficient nondestructive inspection methods capable of detecting conditions known to undermine component integrity. Undetected material faults may ultimately compromise component integrity as evidenced in Figure 4.

Figure 4. Undetected Material Faults. Images courtesy of U.S. Army Program Executive Office - Aviation (2014, 2012).

Main rotor blades continue to appear in quality assessment reports (see Figure 5) as a top customer complaint for good reason—failures are not only costly but result in significant emotional events. Changes in MRB integrity radically impact blade balance and flight characteristics beyond rotor system control and design limitations resulting in the increased risk of catastrophic loss of the entire helicopter and crew members. Component faults identified during field inspections routinely result in PQDR submittals, particularly when the component has little time since new operating hours, or low operating time since last overhaul/sustainment activity.



CCAD Quality Assessment

As Of: Aug 10 2021

Customer Complaints

Possible Production Impact ●							
SOS	CAT 1	CAT 2	CAT 3	CAT 4	CAT 5	No CAT	Value in $
AMC	2	5	4			74	⇧ $12,820,692

PQDRs Open ●		
85	<= 90 days	52
	> 90 & < 120	16
	>= 120 days	17

PQDRs Closed			
Root Cause ●		**Cycle Time** ●	
X - Undetermined	79%	# QDRs closed last QTR	101
Z - N/A	2%	Avg Age at Close (days)	198.1

Top 3 Customer Complaints

in order of CCIR CAT, PQDR CAT and Age

NIIN	Nomenclature	SOS	CCIR CAT	CCIR 1st Report	PQDR CAT	QDR Submit	Qty Def	Total PQDR	Total Value ($)	Age (days)	Resp
016249255	SERVOCYLINDER ASSEMBLY,HY	B17	1	May 12 2021	2	Jul 21 2021	1	1	$18,727.00	20	CCDC
016249557	CYLINDER ASSEMBLY,ACTUATI	B17	1	May 12 2021	2	Aug 9 2021	1	1	$22,011.00	1	AMCOM
011061903	BLADE,MAIN ROTOR	B17	2	Dec 11 2020	1	Jul 22 2021	4	4	$857,800.00	19	CCDC

Supplier Defects

Possible Production Impact ●							
SOS	CAT 1	CAT 2	CAT 3	CAT 4	CAT 5	No CAT	Value in $
AMC	3	27				82	⇧ $5,538,258
DLA	4	1				105	⇧ $753,003
OTHER						5	⇧ $170,219
TOTAL	7	28				192	⇧ $6,461,480

PQDRs Open ●		
227	<= 90 days	81
	> 90 & < 120	20
	>= 120 days	126

PQDRs Closed			
Root Cause ●		**Cycle Time** ●	
X - Undetermined	73%	# QDRs closed last QTR	136
Z - N/A	10%	Avg Age at Close (days)	201.4

Top 3 Supplier Defects

in order of CCIR CAT, PQDR CAT and Age

NIIN	Nomenclature	SOS	CCIR CAT	CCIR 1st Report	PQDR CAT	QDR Submit	Qty Def	Total PQDR	Total Value ($)	Age (days)	Resp
014943019	SEAT,AIRCRAFT	SMS	1	Sep 30 2020	2	Jan 28 2020	2	1	$81,015.98	560	DLA
010785725	INPUT ASSY,LOAD	SMS	1	May 7 2021	2	Apr 2 2020	4	3	$4,151.04	495	DLA
016250436	SERVOCYLINDER	B17	1	May 12 2021	2	Jul 12 2021	1	1	$42,527.00	29	CCDC

Figure 5. Corpus Christi Army Depot Quality Assessment Report. Source: Logistics Data Analysis Center (LDAC) (2021).

The following chapter will address various aspects that are being evaluated in order to determine if improvements to the MRB sustainment methods can be introduced. Chapter III will also identify current methods of inspection that have allowed MRBs to be decommissioned, or dismantled and repaired, simply for means of inspecting primary components. The same chapter will introduce two possible technologies that can be used in conjunction with, or as complete replacements for, current inspections to provide non-destructive data analysis of rotor blade integrity.

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III. RESEARCH METHODOLOGY

In order to provide a base understanding of the approach taken to analyze the current sustainment practices and provide recommended changes for the UH-60 (displayed in Figure 6) MRB this chapter will outline current sustainment practices and data analytic tools used by the Army aviation enterprise. In addition, the chapter will explore alternative technology options for Black Hawk MRB examinations that could provide digital mapping for improvement of current rotor blade inspections. To properly analyze the options available, present-time technologies will be evaluated to determine the possibility of integrating these technologies into the MRB procurement and maintenance processes.

Figure 6. UH-60 “Black Hawk” Helicopter. DOD photo by Gertrud Zach (2013).

There are many approaches to identifying defects in the MRBs. Regularly scheduled maintenance checks are conducted as preventative measures. To properly analyze MRBs during these maintenance checks, inspections are conducted. These inspections are primarily non-intrusive to the MRB, occasionally inspections may result in some form of disassembly or destructive evaluation. Some inspection methods are subjective, while others are very definitive but difficult to conduct due to use of composite materials within the MRB assembly. Examining the current inspection methods seems straight forward; unfortunately, inspection results and analysis remain subjective and vulnerable to human error. Exploring new inspection methods using automated analytical tools may present some solutions, even if introducing additional challenges for gaining enterprise acceptance. MRB analysis will be primarily focused on blades used on the H-60A/L/V versions of the aircraft.

A. MRB CONDITION BASED MAINTENANCE

When considering condition-based maintenance, there are two main methods used today to gauge the present condition of MRBs: preventative maintenance operations and periodic inspections. These inspection methods are detailed within the Army technical manual TM 1-1500-328-23. The standards outlined within the technical manual have been established to provide basic mandatory requirements to which all Army aeronautical equipment is to conform. (DA, 2014a)

1. Preventative Maintenance Operations

Army aviation preventative maintenance systems utilized are expressed in detail within Chapter II of TM 1-1500-328-23. Generally defined preventive maintenance operations utilize a series of inspection systems intended to evaluate component condition throughout the component's life cycle. The Army has used preventative maintenance operations for decades to sustain most of its fielded weapon systems and major system components. Examples of common preventative maintenance inspections conducted on the Black Hawk MRB include pre-flight and thru-flight inspections completed by the aircrew throughout daily operational periods. The intent of these particular preventative inspections is to detect unacceptable component conditions affecting airworthiness that may become apparent after or before completion of other periodic inspections—conditions such as lightning strike, hail or wind or damage suffered during flyable storage and bird strikes or shrapnel damage occurring during flight. The pre-flight and thru-flight inspections are commonly referred to as operator level inspections and are completed using operator checklists and general condition criteria. When a components general condition is suspect, or questionable, then detailed inspections are performed.

Formal periodic inspections are more thorough and involve specified inspection requirements published in component and system level technical manuals. The general condition pre-flight and thru-flight inspections are operationally driven and work in conjunction with detailed periodic inspections to provide a comprehensive preventative maintenance environment, ensuring safe and reliable component operation.

2. Periodic Inspections

There are various periodic inspections to which the Black Hawk MRB is subjected. These periodic inspections include scheduled maintenance inspections, recurring special inspections, and non-recurring special inspections. While each serves the intent of meeting specific inspection requirements, the inspections are performed reciprocally as required to ensure operational integrity of all MRBs. Even though TM 1-1500-328-23 is intended to cover all Army aeronautical equipment, it is interesting to note that the UH-60 platform is the only one that utilizes the periodic/preventive maintenance service (PMS) inspection methods.

Black Hawk scheduled maintenance inspections come in three standardized inspection intervals: preventative maintenance daily (PMD), PMS and phase maintenance inspection (PMI). The PMD is completed at the end of each mission day and provided the aircraft is not flown, remains valid for seven days; the PMS is completed every 40 aircraft hours; and the PMI is completed every 480 aircraft hours or 48 months, whichever occurs first. Each scheduled maintenance inspection utilizes a seven-section checklist to accomplish required inspections. Black Hawk MRB scheduled maintenance inspections are detailed in section 6 (main rotor pylon section) of each maintenance checklist and corresponding component work package.

Recurring special inspections are individual inspections that occur at intervals that are not generally compatible with other scheduled preventative maintenance inspections. Recurring special inspections are subject to tolerance windows allowing inspection accomplishment with flexibility to minimize impact on aircraft availability. Tolerance windows are limited to plus or minus 10% of the inspection frequency—but shall not exceed 5 hours or 30 days.

> For example, if an inspection with a 25-flight hour interval was due at 1550 aircraft hours and it was completed between 1547.5 and 1552.5 hours (25 X 10% = 2.5 hours), the next scheduled inspection would be due at 1575 aircraft hours; or a 75 hour interval was due at 1550 aircraft hours and it was completed between 1545 and 1555 hours (75 X 10% = 7.5 hours not to exceed 5 hours) the next scheduled inspection would be due at 1625 aircraft hours. (DA, 2014a, p. 2-4)

Non-recurring special inspections contain detailed special instructions for equipment subjected to unusual events such as lightning strike, sudden stoppage, hard landing, and over speed check. Aviation messages may direct special inspections to mitigate a variety of concerns—including safety hazards and critical sustainment activity impacting maintenance or system readiness.

The integration of new technologies to perform MRB inspections and provide the improved data analysis is intended to be compatible with the existing preventative maintenance schedules. It is expected that they will support the existing maintenance requirements and provide valuable data collection without component disassembly and tear down of rotor blades in the field.

A relatively recent and successful adoption of new technology to monitor component vibration levels on the Black Hawk is known as the integrated vehicle health management system (IVHMS). The system works in conjunction with scheduled and unscheduled maintenance inspections to mitigate the effects of out of tolerance vibration levels. The continuous monitoring capability and related data analysis assist in decision-making to refine periodic inspections, and enable early troubleshooting of components prior to failure—using near real time data analysis and preset condition indicators. Data is collected continuously during operation and analyzed each day using off aircraft software applications as part of the PMD inspection process. Rotor system vibration and balance data is collected and relatable to each MRB. The IVHMS is providing a condition based maintenance opportunity to refine Black Hawk preventative maintenance inspections.

B. RELIABILITY AND MAINTAINABILITY

1. MRB Inspections

MRB detailed inspection, serviceability and repair criteria are published in work package format and available within each Black Hawk series technical manual utilized by enterprise maintenance activities. The work package format essentially breaks down an inspection method into a work breakdown structure (WBS) for a maintenance/inspection effort to be conducted. For the Black Hawk MRB, a work package may have sections detailing the tools and equipment needed, removal and tear-down instructions, inspection criteria, and assembly and re-installation procedures. In addition to published work packages, depot maintenance work requirement (DMWR) publications provide even more stringent inspection and repair criteria to accomplish a complete overhaul of major components to return the items to wholesale supply inventory in a like new condition.

An example of such depot sustainment repair activity includes MRB cuff replacement. The MRB cuff is the portion of the MRB assembly that attaches each MRB to its corresponding spindle attachment lugs on the main rotor head. The cuff is critically attached to the MRB spar using methods not easily achievable, available, or authorized to be performed by field level maintenance activities. The MRB cuff has a life limit significantly lower than the life limit established for the MRB spar. The MRB assembly is returned to sustainment level maintenance activities when complex repairs and component replacement, or overhaul becomes necessary.

2. MRB Performance Specification

Black Hawk system specifications recognize the MRB as a major component. Major component removal rates are used to quantify component reliability. Removals are categorized utilizing the following terms: mean time between removal (MTBR) and mean time between removals requiring depot return (MTBRRDR). Chargeable removals are those removals resulting in the component being replaced with a like serviceable item. MRBs removed to facilitate phase maintenance inspection and found to be serviceable without repair are not counted as a chargeable removal. Main rotor blade average MTBR and average MTBRRDR inherent values are established at 1700 aircraft-operating hours based on aircraft performance specifications SES-700700 & AVNS-PRF-10002.

3. Historical Rates

As of July 2021, TAMMS records indicate more than 15,000 original-design MRBs have been recorded as gained to inventory since 1977. 4700 MRBs are reported currently installed on various aircraft. 2700 records indicate spare MRBs that are uninstalled and serviceable. Another 4000 are uninstalled unserviceable—awaiting disposition, including field repair or induction into sustainment maintenance activity. Approximately, 3600 MRBs have been retired or scrapped from usable inventory. Item management return data indicates an average of over 40 monthly returns to depot sustainment activities occurring over the last 24 months. Component returns do not always equate to material maintenance induction to repair or overhaul—as noted above some items are retired or scrapped. Likewise, average monthly demands for replacement MRBs do not always equate to the same return rates. This is due to many uninstalled main rotor blades within the enterprise inventory.

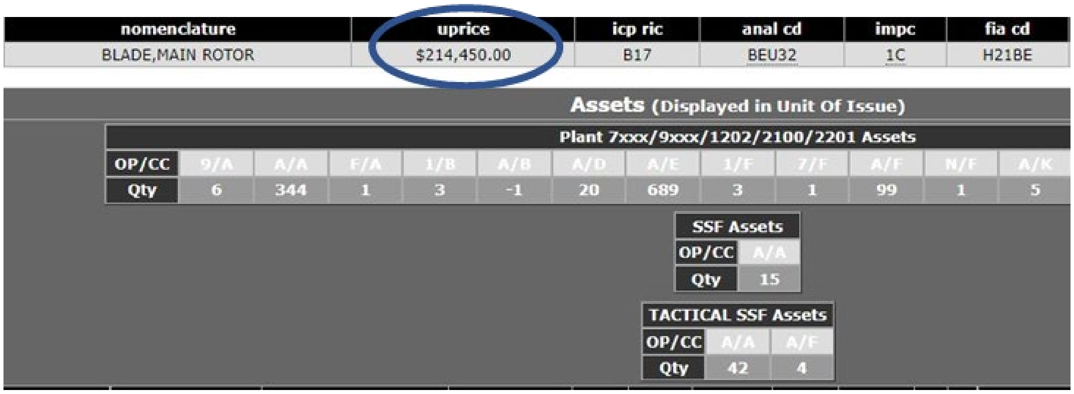
C. SUSTAINMENT

According to the PEO Enterprise Information Systems (EIS) website: Army material item managers utilize the logistics modernization program (LMP) information system to manage material and conduct enterprise material resource planning. The LMP has been in use over two decades and continues to mature to meet changing sustainment and material management requirements spanning inventory, contracting, material repairs and nearly every other facet of logistics integration including Army working capital fund financial management. Direct LMP data access requires unique user familiarization training and access authorizations (PEO EIS, n.d.).

Web based tools were developed to enable other stakeholders within the Army sustainment enterprise to extract LMP data through user friendly interfaces without directly accessing the top tier data server in real time. The LMP data accessed from lower tier servers are routinely updated—but typically no more frequently than 12 hours and often only weekly. The stored static information is sufficient for most material sustainment and forecast planning efforts but not always adequate for moment-to-moment, just-in-time decision-making required of material item managers.

One LMP access tool used to support MRB asset and pricing data analysis included information extracted from the intelligent interactive logistics (I2LOG, n.d.) website. I2LOG has been in use over 17 years; unfortunately for familiar users, this web-based interface is slated for sunset in fiscal year (FY)23 as the Army digital environment continues evolving to address cyber security concerns and limited resourcing.

The highlighted price in Figure 7 reflects MRB retail cost without exchange credit. Exchange credit is awarded for unserviceable turn-ins. Although the MRB is a critical component of the aircraft, the individual cost of a Black Hawk MRB is relatively large when compared to the total aircraft cost. For example, a UH-60L variant helicopter procurement cost is approximately $6M. The material cost of installing a quantity of four rotor blades at approximately $214k each, the entire set of MRBs consume about 14% of the total aircraft cost. Thus, the disposition of an MRB as demilitarized or turn-in and unrepairable is a substantial cost impact.



nomenclature	uprice	icp ric	anal cd	impc	fia cd
BLADE,MAIN ROTOR	$214,450.00	B17	BEU32	1C	H21BE

Assets (Displayed in Unit Of Issue)

Plant 7xxx/9xxx/1202/2100/2201 Assets

OP/CC	9/A	A/A	F/A	1/B	A/B	A/D	A/E	1/F	7/F	A/F	N/F	A/K
Qty	6	344	1	3	-1	20	689	3	1	99	1	5

SSF Assets

OP/CC	A/A
Qty	15

TACTICAL SSF Assets

OP/CC	A/A	A/F
Qty	42	4

Figure 7. Screen Shot of Total Assets Visibility for Original MRB. Source: I2LOG)

1. Material Inventory

In an effort to obtain some cost savings over the procurement of new blades, the Army generates solicitations, and awards contracts, for the overhaul of UH-60 MRBs. The contracts are typically developed as firm-fixed price contracts that can be implemented as an indefinite delivery/indefinite quantity (IDIQ) for a five-year period. The overhaul of a rotor blade consists of rework activities that will result in the rotor blade being reconditioned to a ‘like new’ status. The typical process of an overhaul contract requires the winning bidder to tear down and evaluate each MRB to a point where an overhaul cost estimate can be determined. Per the contract, a maximum overhaul price is determined before any rework is conducted. If the estimated repair work is greater than the maximum allowable overhaul cost, the blade is scrapped, and the Army gets to count the blade towards it minimum required buy quantity per the contract. FY21 data extracted from the I2LOG database and merged into the LMP show the sustainment overhaul price is approximately $114k per MRB. Per I2LOG data, the latest FY21 contract price for a volume buy from the OEM came in at approximately $124k per each MRB.

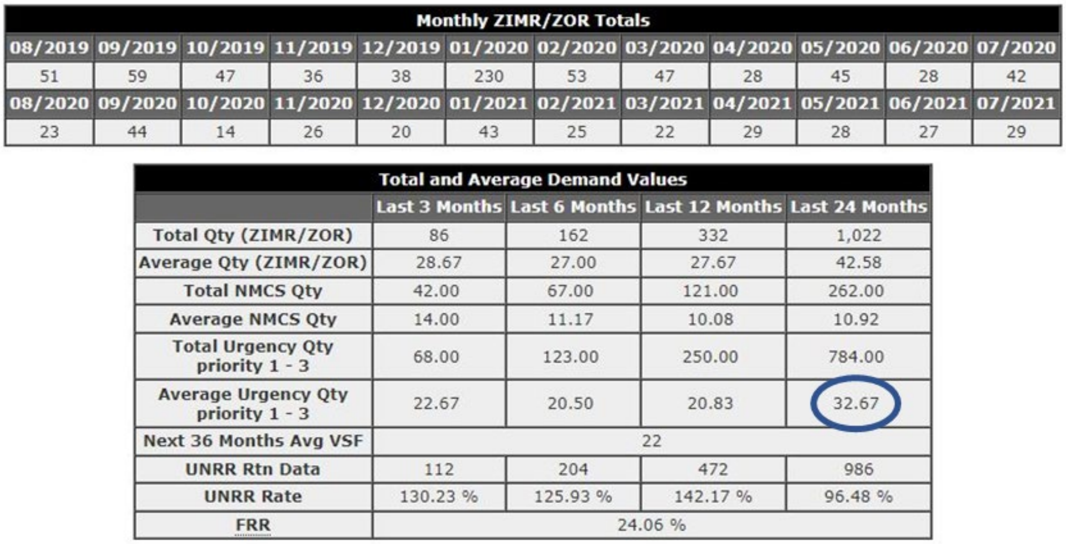
As an example of impact, given a quantity of 700 MRBs on contract for an overhaul and using the current sustainment overhaul cost of $114k per blade, the total contract cost would be expected to come in around $79.8M. If the government is capable of conducting pre-overhaul screenings using new inspection technologies along with existing inspection methods, even an avoidance of sending 70 MRBs (10% impact) could be a cost prevention of around $8M. Thus, implementing the use of a new inspection method could have the capability of providing a ROI rather quickly.

In the interest of preventing unnecessary costs of MRBs being deemed as unrepairable, the new and improved inspection methods outlined in this document are intended to mitigate some of the sunk costs incurred by the Army during routine sustainment practices (such as MRB overhauling). If the Army can conduct inspections that can better determine the operational status of a MRB, then cost avoidance can be achieved by reducing the quantity of MRBs included in a contract.

2. Average Monthly Demand (AMD)

The AMD, provided via the i2log web interface, of Black Hawk MRBs provides the monthly sustainment requirements. These values are important because they provide a realistic demand of the MRBs, which can be used to determine the impact that a field inspection method can have on the fleet. However, inputs to the logistical i2log database are not restricted to field use only values. Values such as lump contract buys may also be included in these numbers. As can be seen in Table 1 under the January 2020 column “01/ 2020,” the monthly requirement is recorded as 230, a value far beyond the typical monthly field requirement. When values in the AMD fields are obviously larger than expected, they are discarded in the count for the AMD. Once the data outliers are discarded from the calculations a realistic AMD can be obtained. As the circled area confirms, the AMD for the Black Hawk MRBs averages a quantity of 33 blades over a 24-month period. This allows us to compute the annual AMD of the Black Hawk MRB at approximately 396.

Table 1. Black Hawk MRB AMD



Monthly ZIMR/ZOR Totals

08/2019	09/2019	10/2019	11/2019	12/2019	01/2020	02/2020	03/2020	04/2020	05/2020	06/2020	07/2020
51	59	47	36	38	230	53	47	28	45	28	42
08/2020	**09/2020**	**10/2020**	**11/2020**	**12/2020**	**01/2021**	**02/2021**	**03/2021**	**04/2021**	**05/2021**	**06/2021**	**07/2021**
23	44	14	26	20	43	25	22	29	28	27	29

Total and Average Demand Values

	Last 3 Months	Last 6 Months	Last 12 Months	Last 24 Months
Total Qty (ZIMR/ZOR)	86	162	332	1,022
Average Qty (ZIMR/ZOR)	28.67	27.00	27.67	42.58
Total NMCS Qty	42.00	67.00	121.00	262.00
Average NMCS Qty	14.00	11.17	10.08	10.92
Total Urgency Qty priority 1 - 3	68.00	123.00	250.00	784.00
Average Urgency Qty priority 1 - 3	22.67	20.50	20.83	32.67
Next 36 Months Avg VSF	22			
UNRR Rtn Data	112	204	472	986
UNRR Rate	130.23 %	125.93 %	142.17 %	96.48 %
FRR	24.06 %			

D. CURRENT NONDESTRUCTIVE INSPECTION METHODS

There are seven primary forms of non-destructive inspection methods as listed in this section: visual, coin tap, bond testing, eddy current, fluorescent penetrant, ultrasonic, radiographic. Each of these inspections provide a different set of information depending on the desired results and may provide a data set that is subjective in nature or very specific and detailed. Each of these inspection methods will be described in more detail in the following paragraphs and be used in comparing technologically advanced inspection methods that this research recommends for use.

1. Visual

The visual inspection relies on an operator to know an MRB well enough to understand what dictates a potential issue. The service team member responsible for performing this inspection is not limited strictly to a visual of the MRB, but may also use their hands to run along the surface of the blade in order to detect irregularities in the material. Because of the subjectivity of this method, it's desired that experienced personnel with practice identifying field issues conduct this test.

2. Coin Tap

The coin tap method of inspection uses a device (typically a smooth disc) to tap on the rotor blade to detect delamination or debond in the epoxy. A coin is typically used in the sustainment community simply because they are readily available amongst service personnel. Due to the composite nature of the UH-60 MRB, a coin tap will provide different types of audible feedback depending on where the coin is being tapped on the blade. Thus, because of the dynamic variability of the MRB and the subjectivity of audible feedback, experienced personnel are desired to conduct the test. In order to detect a defect within the rotor blade, the coin tap inspector relies on a hollow audible tone from a tap on the rotor blade which would indicate an issue.

3. Bond Testing

According to department of the Army technical manual TM 1-1520-265-23 for UH-60 maintenance:

> The bond testing equipment, Bondmaster, used in the procedures in this manual, operates by generating mechanical vibration into the material being tested. This equipment is designed to detect flaws in bonded metallic and composite structures. The instrument can determine bad bonds, delaminations, unbonds, and crushed honeycomb core defects. (DA, 2008, p. 1-21)

> Mechanical vibration energy generated by resonance test equipment can be measured, analyzed by the tester, and then displayed on a screen. There are several ways this energy can be applied to material and then be analyzed. Because bonded metallic and composite material properties differ substantially, no one test method will detect flaws in all types of material. (DA, 2008, p. 1-23)

4. Eddy Current

From department of Army technical manual TM 1-1500-204-23-7 for nondestructive testing and flaw detection:

> Eddy currents are electrical currents induced in a conductor of electricity by reaction with a magnetic field. The eddy currents are circular in nature, and their paths are oriented perpendicular to the direction of the applied magnetic field. In general, during eddy current testing, the varying magnetic field is generated by an alternating electrical current flowing through a coil of wire positioned immediately adjacent to the conductor, around the conductor, or within the conductor.
>
> Eddy current techniques are particularly well suited for detection of service-induced cracks in the field. Service-induced cracks in aircraft structure are generally caused by fatigue or stress corrosion. Both types of cracks initiate at the surface of a part. If this surface is accessible, eddy current inspection can be performed with a minimum of part preparation and a high degree of sensitivity. Unlike penetrant inspection, eddy current inspection can usually be performed without removing such surface coatings as primer, paint, and anodic films. Eddy current inspection has greatest application for inspecting small, localized areas where possible crack initiation is suspected rather than for scanning broad areas of metal for randomly oriented cracks. In some instances, it is more economical to scan relatively large areas with eddy current rather than strip surface coatings, inspect by another method, and then refinish. (DA, 1992, p. 7-1)

5. Fluorescent Penetrant

Army technical manual TM 1-1500-204-23-7 for nondestructive testing and flaw detection describes penetrant inspection as:

> Penetrant inspection is a quick and reliable nondestructive test method used for detecting various types of discontinuities which are opened to the surface of an object or part.
>
> The basic principle of penetrant inspection is to increase the visible contrast between the discontinuity and its background. This is done by treating the

> whole object with an appropriate searching liquid of high mobility and penetrating power and then encouraging the liquid to emerge from the discontinuity to reveal the flaw pattern to the inspecting personnel. (DA, 1992, p. 3-1)

Fluorescent penetrant field inspections applied to Black Hawk MRB are generally limited to attaching hardware or used as back up to validate surface discontinuities identified in components through visual inspection or other nondestructive inspection methods. An example of effective fluorescent penetrant use providing increased visibility is evident in the following Figure 8.

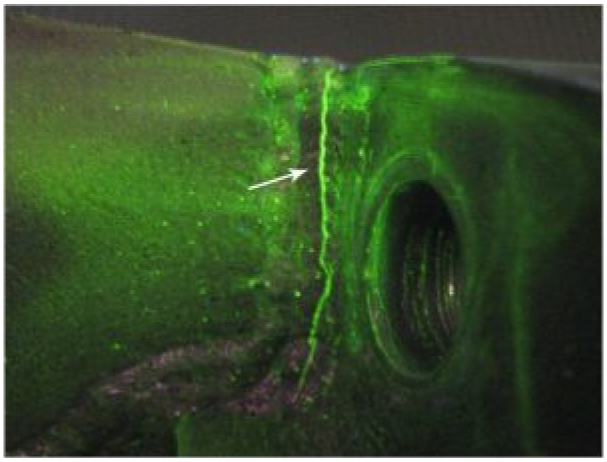


Figure 8. Fluorescent Penetrant High Contrast Surface Discontinuity. Source: Sentinel, https://www.sentinelltd.co.nz/ (2021).

6. Ultrasonic

Army technical manual TM 1-1500-204-23-7 states:

> Ultrasonic is the name given to the study and application of sound wave frequencies higher than those to which the human ear can respond, 20,000 Hz (hertz or cycles per second). In contact ultrasonic testing the most used frequencies range is from 2.25 to 10 MHz (megahertz or million cycles per second). Frequencies below this range and up to about 25 MHz are also used on occasion.
>
> Ultrasonic detection equipment has made it possible to locate defects in all types of parts without damaging the part being inspected. Minute cracks,

> checks, and voids, too small to be seen by X-ray, are located by ultrasonic inspections. Access to only one surface of the part is necessary.
>
> The sound beam is not a straight sided projection of the face of the search unit having uniform intensity. The sound beam spreads out beyond the face of the search unit and varies in intensity. This causes dead zones and other problems. (DA, 1992, p. 6-1)

7. Radiographic

For radiographic inspection methods, technical manual TM 1-1500-204-23-7 describes the method as:

> X-ray and gamma ray radiographic inspection utilizes the penetrating power of radiation to reveal the interior of objects as recorded on film. The extent of recorded information is dependent upon three prime factors which are responsible for an object to absorb radiation to varying degrees. These are:
>
> - The composition of the object.
> - The product of the density and the thickness of the object.
> - The energy of the X-ray gamma rays which are incident upon the object. Its discontinuities cause an apparent change in these characteristics and thus make themselves detectable.
>
> Radiography is a useful non-destructive inspection method designed to detect internal discontinuities is many parts and substances.
>
> Radiography may be applied to the inspection of castings, welds, and assembled components. Various metals, both ferrous and nonferrous, as well as nonmetallic metals such as ceramics and plastics, can successfully be inspected.
>
> Radiography is not a cure-all and should be used only when conditions are satisfied. Multiple film techniques and other special methods make radiography a versatile tool for evaluation. (DA, 1992, p. 5-1)

E. POSSIBLE ADVANCED TECHNOLOGY INSPECTION SOLUTIONS OR APPLICATIONS

The two technology areas that will be explored as possible partial replacement methods for current inspections are shearography and thermography. Each of these methods could be examined as a singular solution to replace a majority of the current subjective inspections or a combination of the two to provide a holistic view of an MRB. Both methods offer benefits extending beyond current inspection methods but may have drawbacks such as substantial resource investments and a shift in inspection professions to an engineering expertise. Both technologies noted can be used to generate a digital map. The digital mapping method could be inserted into an automated comparator software tool to provide near instantaneous unbiased feedback to the inspection crew responsible for the MRB integrity.

One of the primary benefits of both partial replacement methods is their non-destructive nature they bring to the table. While some of legacy inspection methods are non-destructive, none of them alone offer a full solution without some form of destructive maintenance to investigate suspect failures. Other benefits in using newer technologies is the reduction in time it takes to perform an inspection, the level of detail provided from digital processing, and the recurring reliability.

Although current MRB inspection methods evaluated in this research occur at a depot/maintenance level, the possibilities of exploring newer technologies could preclude the need for removal of rotor blades from the aircraft. The reason for exploring depot/sustainment maintenance level inspections while on the aircraft can provide substantial ROI if the requirement to remove blades no longer exists.

1. Shearography

Shearography, or speckle pattern shearing interferometry, can be described simply as a light refraction measurement methodology. Renishaw states on their website that interferometry is defined as "a measurement method using the phenomenon of interference of waves (usually light, radio or sound waves)" (Renishaw, n.d.). More descriptively, TWI Ltd. defines shearography as a technology that "uses coherent laser light in a similar manner to holographic interferometry to create a visual representation of a test object." (TWI, n.d.). As an example, shearography is capable of producing images like the one shown in Figure 9. It also shows a 14 ft. long aircraft flap that was tested in a vacuum shearography chamber with automatic image stitching. In this particular example, over 90 spots of delamination were detected using shearography. Due to the ability of shearography technologies to examine composite materials like a rotor blade as seen in Figure 10, this becomes an ideal inspection method for Black Hawk MRBs.

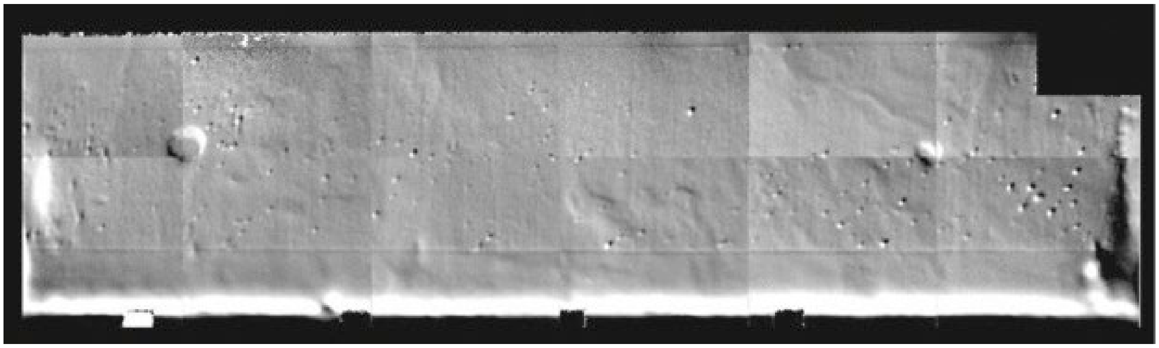


Figure 9. Shearography Used on an Aircraft Flap. Source: Science Direct (2018).

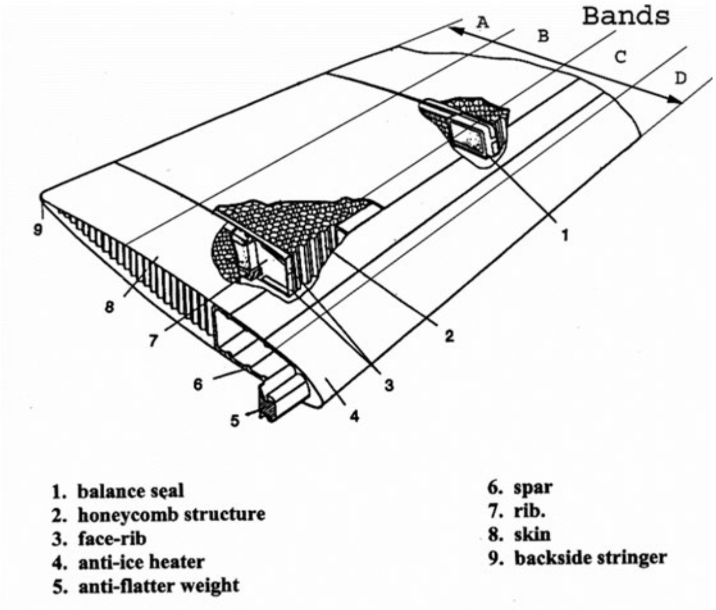


Figure 10. Representative Composite Structure of a Rotor Blade. Source: ResearchGate (2021).

Instead of dismantling an MRB to examine a possible delamination of materials, shearography can be utilized to provide a visual (or digital) image of the rotor blade. If shearography confirms a suspected portion of the blade needing repair, the repair job becomes minimalistic. For example, if a coin tap inspection leads a maintenance crew to suspect delamination interior to the MRB, large area of the blade would be disassembled, or dismantled, in order to find the suspected area of delamination. Since shearography provides a collective data set with high-fidelity, the defect can be located with pin-point accuracy preventing a larger than necessary portion of the MRB to be repaired.

2. Thermal Imaging (Thermography)

Thermography is a more common industry inspection method that captures differences in heat signatures using infrared radiation. Thermography is more commonly known for its use in the medical industry for identifying health concerns. More specifically, as infrared technologies improve, it is becoming widely used to identify signs of breast cancer. Although thermography has a strong foothold in the medical industry, it is also used in non-medical activities such as security and construction applications. This is an emerging technology that the renewable energy industry is working to apply to wind turbine blades. Because of its non-destructive applicability, thermography can be a valuable preventative maintenance tool for wind turbine blades while in operation. Similar in design to UH-60 MRBs, wind turbine blades can be used as a comparable test item as can be seen in Figure 11. The figure shows the results from using thermography on a wind turbine blade at three different times throughout the day. Part (a) is the result of a thermographic image taken at 9am in the morning, (b) was taken at noon, and (c) was taken at 6pm. The reason for capturing images at multiple times is the difference in heat signature provided by the suns radiation. As can be seen in the image below, additional applied heat can provide more spectral density allowing for better detection of flaws.

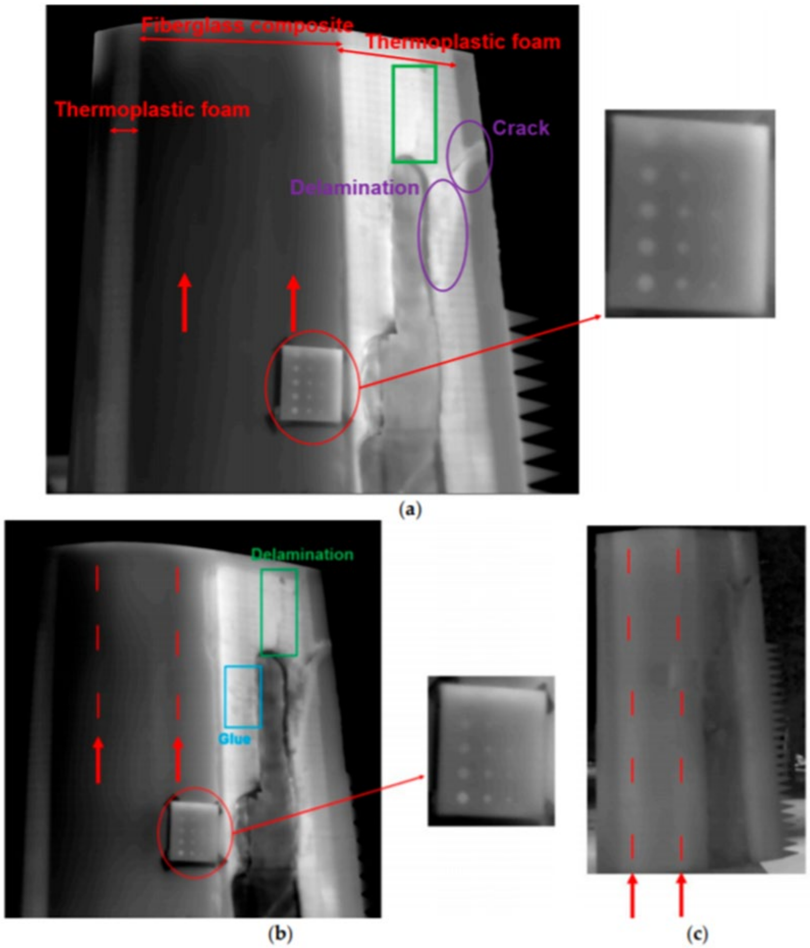


Figure 11. Thermographic Results for a Wind Turbine Blade. Source: Hadi Sanati, David Wood, and Qiao Sun (2018).

Thermography tests on wind turbine blades has produced several valuable papers on the benefits and limitations of using this method. One of the benefits is that thermography can be used during active rotation of rotor blades reducing the need for disassembly from the aircraft. The rotor blades would be required to rotate at a slower pace than in flight. Like shearography, thermography works best when the unit under test is subjected to a stress. Instead of using external mechanisms to stress the blade by bending or twisting, the rotation would provide the necessary stress levels to capture meaningful data. With a man in the loop, the speed of rotation can be controlled from the cockpit in a reliable manner. Another aspect of thermography, although not specifically required, that would improve the reliability of consistent data sets is the application of heat to substantiate detection of rotor blade defects. Thermal imaging can be conducted without the application of heat; however, the data sets and images produced can be more subjective at cooler temperatures and allow for human error.

The following chapter, Chapter IV, will take a deeper dive into the recommended application of shearography and thermography as possible replacements for some of the current inspection methods. At a minimum, we will explore opportunities for the new technologies to be used as additive data analysis tools to improve current data sets. The data collected during shearography and thermography tests can be used to generate a visual image, or digital map, for ease of comparison to baseline information sets. Digital mapping represents an opportunity space that the DOD can take advantage of in order to provide high-fidelity digital data. This data can be used to provide substantial improvements to inspection methods with the intent of reducing the logistics footprint. Opportunities for improvement exist in the realm of inspection time, inventory improvements resulting from the reduction of destructive tests, and a substantial cost savings associated with procurements and repairs.

IV. RESULTS

A. COMPARATIVE IMAGING PROCESS

In order to improve the inspection methods for the Black Hawk MRB, it is recommended that the two inspection technologies listed earlier as shearography and thermography be considered for adoption. Each of these inspection methods can be used to generate digital images, or maps, for comparison. For the process to be beneficial and useful to the Black Hawk logistics and sustainment communities, standards should be established amongst the original equipment manufacturer (OEM) and the Army. For the purposes of this document, it is recommended that shearography and thermography be used to generate baseline images from the OEM and sustainment images after the MRBs are placed into service. Once a new inspection technology is adopted, the potential exists for a sustainment digital map of a MRB to be compared to a baseline map in order to detect differences over time. It may prove difficult to alter the current method of inspecting rotor blades, but it is the intent of this research to show how beneficial such changes can be. Not only does the implementation of new inspection technologies provide an opportunity to improve costs, they may also prevent catastrophic failures seen in the field by catching issues that otherwise may not be identified.

1. Digital Mapping and Comparison

When inspections lead to data sets that are developed digitally and stored as images, they can be used as resources to feed into a comparative tool in order to analyze and calculate the difference between images. In order to understand the basics of how two images can be compared to one another, a general description of how a digital image is computationally generated is provided. Every digital image is the result of millions of picture elements, or pixels, which are combined to form a single digital image. Each digital pixel is displayed as a color that is determined based on a combination of binary numbers. Variations and composites of colors combined are what creates an image that can be easily distinguished by the human eye. However, at the root of every computer operation is a binary number; for images, it's no different. Each variation of color that can be recognized in a digital image has a representative binary number associated with it.

In order to compare two images to one another a software tool can be used or a person can visually compare the images. Unfortunately, anytime a human is included in any process loop, there is room for human error and the possibility of subjectivity. Whether a fault in comparison be human error or subjectivity, both induce the risk of missing possible issues identified by variations in imagery. As with any intricate process where a human is asked to distinguish between right and wrong, experience becomes a necessity and can only be obtained after time. However, a benefit to using a human in the loop is the ability to catch large variations in images that can be obvious to even the most novice operator. Therefore, it only make sense to use a human in the loop and a software tool as complimentary processes.

In order to digitally compare two images to one another, each pixel per image is compared to the same pixel in a comparable image. Instead of a computer working to determine the variation in brightness and contrast from pixel to pixel, it actually calculates the difference in binary values from pixel to pixel and displays a new image that highlights variations. This is the general process that is used anytime two images are compared to one another. This same process can be developed into a software tool with a graphical user interface that can be used by virtually anyone.

The benefits to using a software tool is that it can catch differences down to a single pixel, which could easily be missed by a person inspecting an image. Using a person to compare two images has benefits too; a person can easily distinguish between two images when there is a substantial difference. In order to prevent unnecessary inspection scans or rework, it is recommended a person conduct an initial evaluation to determine large image discrepancies between two images and then use the software tool to identify any minuscule deltas between pixels.

2. Baseline Imaging

Currently, the OEM provides a certificate of component quality assurance and compliance with manufacturer drawings and specifications. No digital imaging of the MRB is provided to establish a material baseline at gain to inventory. Creating a baseline image ensures a tangible record of component configuration conformance upon delivery to the government. Benefitting all stakeholders by documenting component attributes during the gain to government inventory.

3. Sustainment Imaging

Once the Black Hawk MRBs are gained inventory and installed for use, the recurring and time cycle inspection clock begins. For every recurring and time cycle inspection, this research looks at injecting a new inspection technology into the process. The two recommended technologies defined earlier in this document as shearography and thermography will be examined as 1) possible inspection methods that can be used to identify failures that may not be captured during routine inspection practices and 2) tools to generate digital maps to track changes in MRBs over time. Both of these options have the opportunity to provide the defense industry a substantial return on investment (ROI).

a. Possible Application of Shearography

Unlike other inspection methods, such as a visual examination, that could allow the MRB to remain virtually untouched, shearography requires the test unit be stressed in order to obtain a reliable data set. Implementation on an MRB would require an image be taken during the application of specific wavelengths of light in a normal state. The MRB would then be held in a stressed state, by either twisting or bending, while a second image is taken. The delta between the two images would then provide a speckle pattern image (another name for shearography). This new speckle pattern image would provide quick and visible feedback to a maintenance crew. Two possible methods for applying shearography to the Black Hawk MRB would be to have the rotor blade removed from the aircraft for inspection or conduct a field level inspection at the fully installed rotorcraft level. Although the removal of the MRBs is a viable option for improving inspection techniques and is briefly mentioned below, we will examine the application and benefits of performing on-aircraft inspections in order to recognize the substantial ROI these changes can have.

With the MRB removed from the aircraft, the hardware and tooling needed for shearography would allow for a smaller footprint. The MRB could be affixed to a rigid platform on one end while the opposite side of the MRB is coupled to a torque motor that would provide the stressing required by shearography. Understanding the MRB stress limits would need to be taken into careful consideration to ensure no damage to the rotor blade. Cameras could be placed in multiple locations to provide a 360° view of the MRB while subjected to light waves. An article written in 2003 by R. Krupka, T. Waltz, and A. Ettemeyer regarding the *Industrial Applications of Shearography for Inspection of Aircraft Components* validates shearography as an improved non-destructive test (NDT) for aircraft components, specifically helicopter rotor blades. This article provides examples of shearography being applied as inspection methods for rotor blades as seen in Figure 12. Figure 12 shows an inspection of a helicopter rotor blade inside a vacuum chamber that is using shearography to detect any deformations and/or delamination (Krupka, 2003). In this particular example, the vacuum chamber is applying the stress required to conduct a non-destructive shearography test.

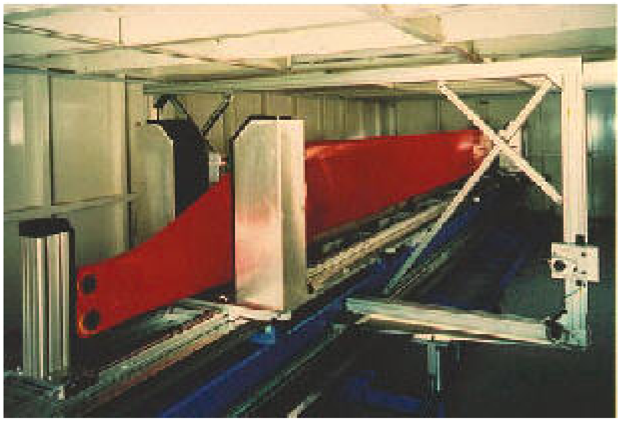


Figure 12. Shearography Applied to a Rotor Blade Inside a Vacuum Chamber. Source: Krupka (2003)

In a similar fashion, the MRB could also be inspected at a field level while installed on the aircraft. Inspecting a MRB while on the aircraft will pose a significant challenge in changing the status-quo associated with typical inspection routines. Typically, the MRBs are removed, not only to provide for a better inspection, but also so the aircraft is not subjected to anything that could pose a risk of damage. Due to the substantial cost of an aircraft, any risk of damage is typically mitigated via removal of the hazard. In this particular scenario, the hazard would be performing an inspection while the rotor blades remain intact to the aircraft. However, given due diligence and design, it can be argued that the probability of risk can be mitigated down to a negligible level.

Currently, conducting an on-aircraft inspection using shearography would require a substantially different arrangement of equipment that is required for the inspection, but would offer the benefit of a quick system level inspection represented in Figure 13. The aircraft could be brought into a hangar where each of the UH-60 four rotor blades would be rotated to a side of the hangar housing the shearography apparatus. In this scenario, the aircraft could be used to apply a torque to the MRB or could be used to hold the MRB rigid. In either application, a connection would be made to the rotor blade at the opposite end of the main rotor mast. At the tip of the MRB, a torque motor could be used to bend or twist the MRB or the tip of the MRB could be coupled to a rigid collar to hold the blade. See Figure 13 for a depiction of a possible test configuration at the full assembly level.

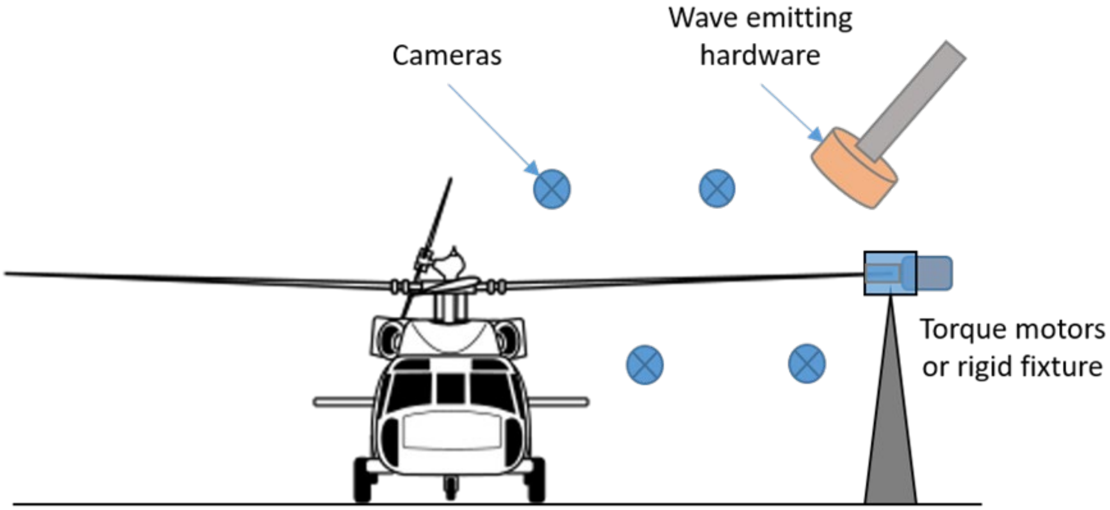


Figure 13. Depiction of Shearography Test Configuration for a Full Assembly. Adapted from *Introduction to Aerospace Engineering with a Flight Test Perspective* (2017, p. 29).

Per The Welding Institute limited (TWI Ltd.), an innovative company with an expertise in material analyses, given the proper equipment an inspection can conducted at nearly 1m^2 per minute using shearography (TWI Ltd., n.d.). At an approximate size of 5m^2 [length of the chord] x [length of the MRB], the Black Hawk MRB active inspection time using shearography could be as little as 5 minutes per blade. Comparing the time to inspect a MRB while installed on an aircraft to the time it takes to remove, package, ship, setup, and inspect a MRB using the current methods, an inspection can be reduced from days to minutes. Not only is there a potential for substantial cost savings in labor, there is a significant reduction in the logistics footprint currently required to inspect a MRB.

b. Benefits of Shearography

As shearography technologies continue to advance and industries take advantage of it NDT capabilities, the benefits of using the inspection methods can be observed. According to an article written by John Newman for Quality Magazine in 2009, shearography became the first certified NDT method for the National Aeronautics and Space Administration (NASA) to inspect space shuttle foam (Newman, 2009). Some of the benefits of shearography that could recognized immediately after integration into the inspection process of MRBs would be the improvement of cost, schedule and quality.

(1) Cost

Earlier in this document, in Chapter III C.1., a hypothetical example is given with a 10% reduction in overhaul costs from a lot consisting of 700 MRBs that provided a savings of $8M. Although an estimated cost of procuring and installing a shearography system for examining MRBs would need to be acquired through market research and request for proposals, conversations with Army material analysis experts express that a system can be assumed to cost around $10M. Given that a shearography system procurement cost would consume $10M in investment funds, the ROI would be recognized rather quickly if the system could reduce the return of a MRB lot by 10%. It is reasonable to assume that a 10% reduction of MRB overhaul contract quantities could be recognized simply because the rotor blades are critical and an expensive component of the helicopter, which increases the chance of an operator notating a defect based solely on suspicion.

(2) Schedule

If the inspection of a MRB was conducted on the aircraft, as recommended, the time to conduct a routine inspection and analyze the results could be reduced from days to minutes. This reduction in schedule would substantially impact a fleet via a reduction in maintenance crew time and the time associated with the logistics footprint of removing and shipping a MRB. Although time can always be converted to dollars, the benefit of reducing the inspection time from days to minutes alone is substantial enough to warrant an investment into a technology such as shearography.

(3) Quality

As pointed out in a NASA article authored by James L. Walker and Joel D. Richter, shearography is not an ideal inspection method for detecting defects deep within a system; however it is ideal for detecting issues just beneath the surface of a component, such as delamination (Walker, n.d. p 4). Delamination is known as a common failure mode for Black Hawk MRBs in the field, thus shearography offers promising improvements for catching issues that current inspection methods may miss. As noted in the John Newman Quality Magazine article mentioned above, shearography has an extreme sensitivity such that it could catch defects down to 10 nanometers during an inspection (Newman, 2009). Using this technology would provide a more thorough and systematic approach to capture defects of a composite rotor blade, as seen in Figure 10, which would improve quality of MRBs via inspection practices in the field.

c. Possible Application of Thermography

Similar to the shearography methods of testing, thermography could be applied at a MRB level or at the aircraft level. One of the primary benefits of thermography is that the rotation of the blades would provide an acceptable stress level that would mitigate the need for external torque devices. For the purpose of this research, we will examine the possibility of using thermography at the aircraft level with possible controls in place to provide better data sets. For the same reasons as discussed for using shearography at the aircraft level, modifying status-quo inspection methods to include thermography at the system level would be difficult as it would subject the aircraft to undesired risks. However, if the Army is willing to trade negligible risks for cost and time savings coupled with quality improvements during inspections, thermography offers the same benefits as shearography.

In order to control the test environment, it would be recommended that the rotor blades be subjected to a radiant heating mechanism while in a slow rotation. Although not needed, a slow rotation would supply a reasonable amount of stress to a rotor blade, which can provide results that are easier to analyze both visually and via a software tool. A method of producing a test configuration would be to install an overhead radiant heater while capturing thermal images of the rotor blades in rotation. Although the details of determining what the best speed of rotation is, how to rotate the blades, and the amount of applied heat required to provide legitimate results still need to be determined through analysis, it is reasonable to assume that this could be conducted given proper attention to analysis. A depiction of a possible test setup can be seen in Figure 14.

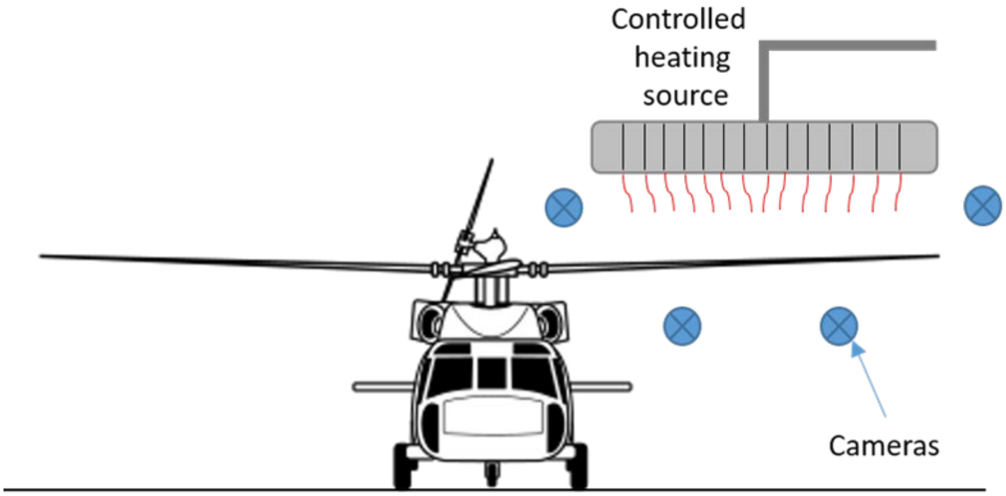


Figure 14. Depiction of a Controlled Thermography Test Configuration. Adapted from *Introduction to Aerospace Engineering with a Flight Test Perspective* (2017, p. 29).

With improvements in instrumentation that can be used to conduct thermography scans, a leading industry organization Thermal Wave Imaging (TWI) is pushing the limits for how thermography is used in the defense industry. Like shearography, thermography is also a NDT that can be used to detect anomalies or defects of composite materials. As depicted in Figure 15, TWI is pushing to advance inspection techniques in the field even with new and emerging weapon systems such as the future vertical lift platforms. Although Figure 15 shows an inspection on the body of an aircraft, according to TWI the technology is best fit to inspect composite images for impact damage, delaminations, water ingress, foreign object debris detection, thickness measurement, porosity, and disbonds (TWI, n.d.). Similar to the honeycomb structure of a rotor blade, TWI shows an example on their website, Figure 16, of how thermography can assist in detecting trapped water internal to a honeycomb structure.

Figure 15. Large Area Inspection Concept as presented on the TWI website. Source: TWI, https://www.thermalwave.com/technology/.

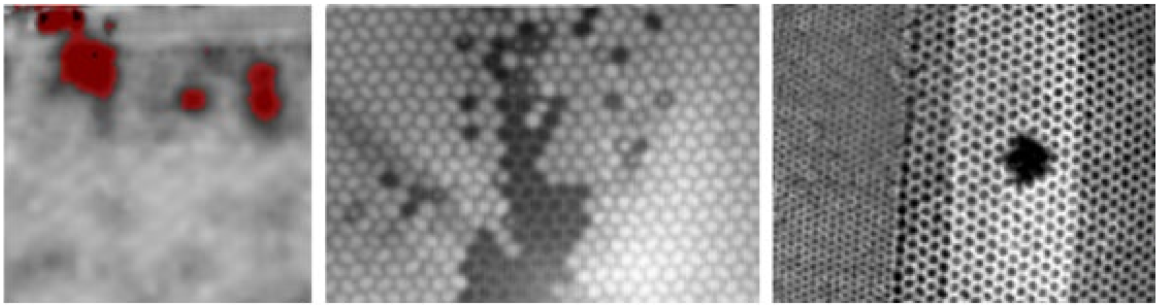


Figure 16. Trapped Water in Honeycomb Structures. Source: TWI, https://www.thermalwave.com/applications/#aerospace.

d. Benefits of Thermography

Anytime a new and proven technology is properly introduced into an existing and outdated process, it almost always adds a ROI that exceeds the investment cost. Fortunately, since its discovery in the early 19th century thermography has been an advancing and widely used technology. The historical use of thermography has allowed industry to generate and compile information that validates thermography as a beneficial tool. In the same way that shearography was examined with regards to cost, schedule and quality, this research examines thermography in the same way.

(1) Cost

Using the same hypothetical example that was used to determine a potential cost savings associated with a reduction of blades on an overhaul contract, it is reasonable to assume that similar cost preventative measures could be calculated to be around $8M. The cost of procuring and investing into a thermographic test setup was determined via conversations with material analysis experts to cost approximately $8M (slightly cheaper than its shearography counterpart). According to the small unmanned aircraft system (sUAS) news website on the business of drones, substantial savings have been noted by several industry organizations. One client managing a large portfolio of solar modules provided feedback to sUAS news stating that they save approximately $383k annually by repairing defective solar panel modules that would not have been discovered during hands-on inspections (sUAS, 2020). Although the cost savings that are recorded on the website are cost savings realized using thermographic inspections of solar modules, that same data can be translated to the defense industry for rotor blade inspections.

(2) Schedule

The same organization listed above, sUAS, lists on their website that “the greatest advantage of aerial thermography is its speed. A manually piloted drone is able to collect data 10 times faster than a technician on the ground within 97% accuracy” (sUAS, 2020). This technology is being applied via drones to several square miles covered with solar modules. Thus, if applying this technology to a small area, such as the size of a rotor blade (approximately 5m^2), the time of inspection would be reduced dramatically considering that the rotor blade does not need to be removed, packaged, shipped, and inspected. Similar to shearography, the time savings can be seen as a reduction from days to minutes.

(3) Quality

As noted above on the sUAS website, thermography offers a 97% accurate solution for inspection processes. Moreover, a published Multidisciplinary Digital Publishing Institute Sensors article by Francesco Ciampa, Pooyah Mahmoodi, Fulvio Pinto and Michele Meo titled *Recent Advanced in Active Infrared Thermography for Non-Destructive Testing of Aerospace Components* analyzes and details the quality benefits of using thermography as a potential inspection source for composite aerospace components. Using the analysis in article as validation criteria, it states that “material-based thermography methods have proved to offer a fast, low power, accurate and reliable assessment of delamination and cracks in aerospace composite components” (Ciampa, 2018, p. 30).

B. PROCESS MAPPING

Each blade currently goes through a cycle from a defined process. Figure 17 depicts at a given period; the blade must be visually inspected and move onto a deeper examination if there is sufficient wear and tear that is observed. The process identifies stress state from possible fatigue failure. MRBs that go through this process mapping routine still go through manually. Any correlation is identified by an individual or individuals doing the mapping.

The key issue with this process is human error. There is not an automated process that can compare images or identify patterns at any given combination of causes. The manufacturer’s MRB historical data may or may not provide sufficient data to provide the inspection team a predicted or realized pattern of stress fatigue.

Figure 17 furthermore illustrates where a person is required to examine a component consisting of composite material. As mentioned before, the complexity of identifying flaws or defects on a modern MRB is very challenging and subject to human error due to its composite nature. At this point in time, the Army does not possess a computer system that can assist in the comparison process; let alone a means of correlating the data since past findings are manually scanned and archived into a resting database. During all inspections the data collected and repairs initiated end up being logged into a RIMFIRE report. An extraction from a RIMFIRE report can be seen in Figure 18. This current process mapping is plagued with inconsistent information and data that is not easily accessed for analyzing present maintainability concerns and predicting future component failures. As can be seen in the RIMFIRE report extract, it would be extremely difficult to correlate incidents and repairs over time via sorting through PDF documentation.

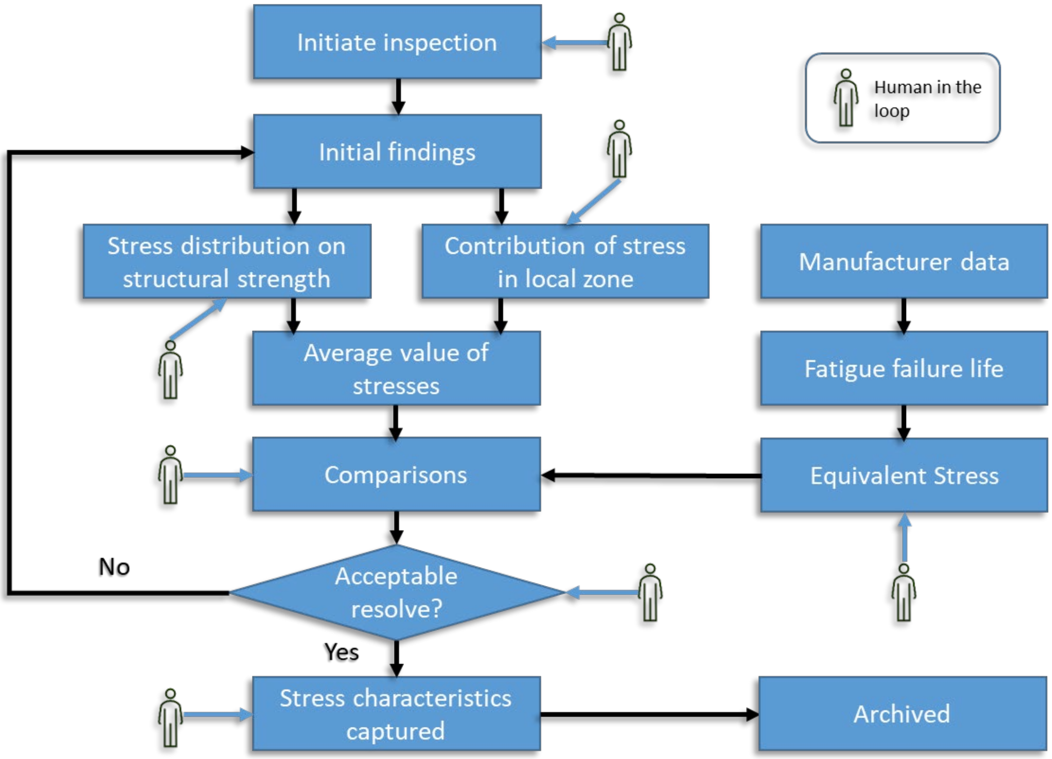
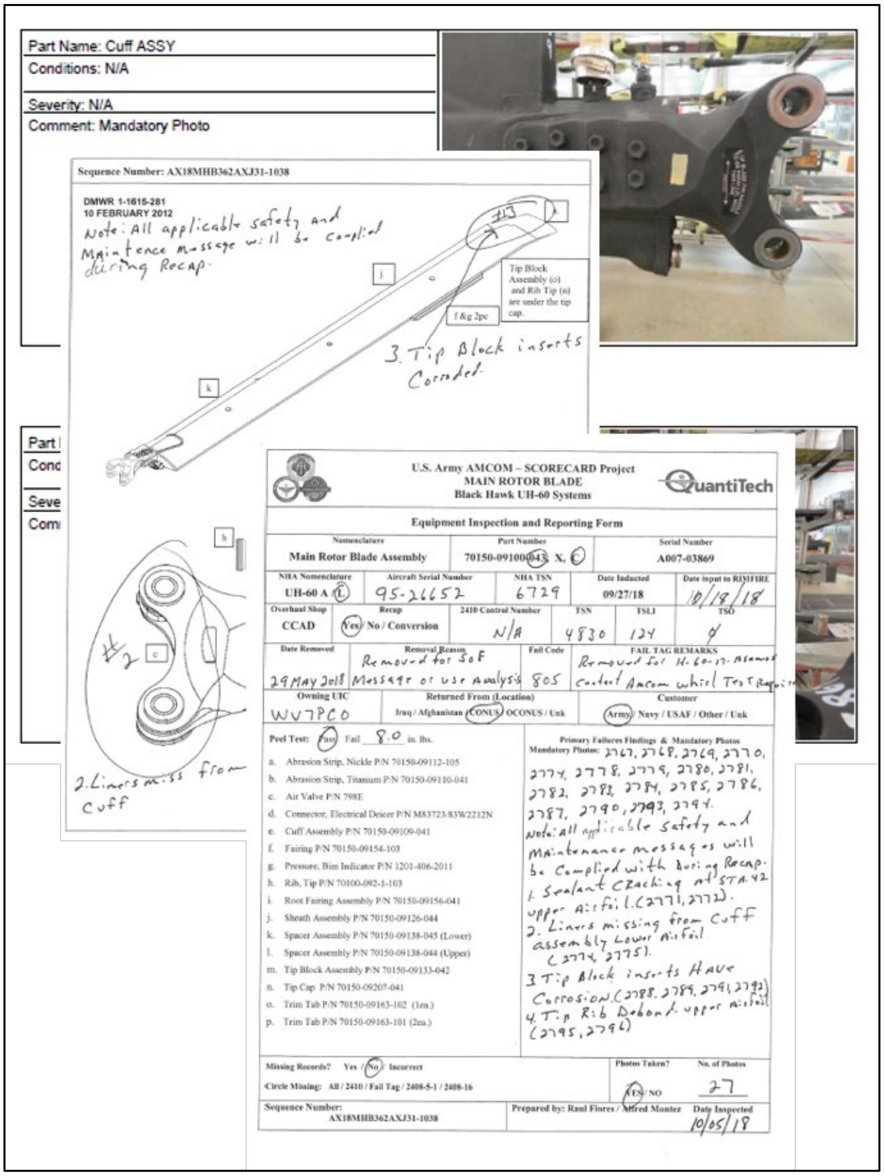


Figure 17. Current process of identifying characteristic stress of the component. Adapted from *A Modified Stress Field Intensity Approach for Fatigue Life Prediction of Components* (2020, p. 4).



Part Name: Cuff ASSY
Conditions: N/A
Severity: N/A
Comment: Mandatory Photo

Sequence Number: AX18MHB362AXJ31-1038

DMWR 1-1615-281
10 FEBRUARY 2012

Note: All applicable safety and Maintence message will be complied during Recap.

Tip Block Assembly (o) and Rib Tip (n) are under the tip cap.

3. Tip Block inserts Corroded.

2. Liners miss from cuff

U.S. Army AMCOM – SCORECARD Project
MAIN ROTOR BLADE
Black Hawk UH-60 Systems

QuantiTech

Equipment Inspection and Reporting Form

Nomenclature Main Rotor Blade Assembly	Part Number 70150-09100-043, X, C	Serial Number A007-03869			
NHA Nomenclature UH-60 A / L	Aircraft Serial Number 95-26652	NHA TSN 6729	Date Inducted 09/27/18	Date input to RIMFIRE 10/18/18	
Overhaul Shop CCAD	Recap [✓ Yes] / No / Conversion	2410 Control Number N/A	TSN 4830	TSLI 124	TSO 0
Date Removed 29 MAY 2018	Removal Reason Removed for SoF Message or use Analysis	Fail Code 805	FAIL TAG REMARKS Removed for H-60-17-Asames contact Amcom whirl Test Requir		
Owning UIC WV7PC0	Returned From (Location) Iraq / Afghanistan / [✓ CONUS] / OCONUS / Unk	Customer [✓ Army] / Navy / USAF / Other / Unk			

Peel Test: [✓ Pass] Fail 8.0 in. lbs.

a. Abrasion Strip, Nickle P/N 70150-09112-105
b. Abrasion Strip, Titanium P/N 70150-09110-041
c. Air Valve P/N 798E
d. Connector, Electrical Deicer P/N M83723/83W2212N
e. Cuff Assembly P/N 70150-09109-041
f. Fairing P/N 70150-09154-103
g. Pressure, Bim Indicator P/N 1201-406-2011
h. Rib, Tip P/N 70100-092-1-103
i. Root Fairing Assembly P/N 70150-09156-041
j. Sheath Assembly P/N 70150-09126-044
k. Spacer Assembly P/N 70150-09138-045 (Lower)
l. Spacer Assembly P/N 70150-09138-044 (Upper)
m. Tip Block Assembly P/N 70150-09133-042
n. Tip Cap P/N 70150-09207-041
o. Trim Tab P/N 70150-09163-102 (1ea.)
p. Trim Tab P/N 70150-09163-101 (2ea.)

Primary Failures Findings & Mandatory Photos
Mandatory Photos: 2767, 2768, 2769, 2770, 2774, 2778, 2779, 2780, 2781, 2782, 2783, 2784, 2785, 2786, 2787, 2790, 2793, 2794.
Note: All applicable safety and Maintenance messages will be Complied with During Recap.
1. Sealant CRacking at STA.42 upper Airfoil. (2771, 2772).
2. Liners missing from Cuff assembly Lower Airfoil (2774, 2775).
3 Tip Block inserts Have Corrosion. (2788, 2789, 2791, 2792)
4. Tip Rib Debond. upper Airfoil (2795, 2796)

Missing Records? Yes / [✓ No] / Incorrect
Circle Missing: All / 2410 / Fail Tag / 2408-5-1 / 2408-16
Photos Taken? [✓ YES] / NO
No. of Photos 27
Sequence Number: AX18MHB362AXJ31-1038
Prepared by: Raul Flores / Alfred Montez
Date Inspected 10/05/18

Figure 18. Extracts from a RIMFIRE Report. Adapted from RIMFIRE *Teardown Analysis Full Report for Main Rotor Blade* (2018).

V. CLOSEOUT

1. Recommended Changes

After researching and analyzing current sustainment and maintenance practices used on Black Hawk MRBs, the primary areas for recommended change are:

- inclusion of new inspection technologies to create digital maps
- generation of a baseline digital image of each MRB using new technology
- generation of sustainment digital images for each MRB
- acquisition of a software tool to analyze digital maps

After summarizing these recommendations, we explore potential areas for further research. A conclusion will be provided at the end of this chapter to summarize this research.

a. New Inspection Technology

There are existing technologies which might be applied to more efficiently evaluate component design integrity throughout the component life cycle. Our study explored utilizing shearography or thermography to generate a digital map to systematically measure deviations in MRB integrity during sustainment level maintenance activity. These technologies can be used to update and renew an outdated and unreliable combination of inspection techniques that allow MRB failures to occur in the fleet. The outdated inspection methodologies also allow for an unnecessary quantity of MRBs to be contracted for an overhaul simply because the technologies to properly inspect composite materials has not been integrated in the Army sustainment model. The technologies introduced in this research provide the capability of the Army to generate digital maps that can be used for analysis or comparison to older maps (or images). This mapping can be used during routine checkups and identify any degradation or defects while in service. Digital mapping may prove vital in safeguarding serviceability and reliability of MRBs once placed into service.

It is highly recommended that at least one of the inspection technologies, shearography or thermography, be inserted into the existing inspection processes.

b. *Baseline Digital Imagery*

For each Black Hawk MRB, it is recommended a baseline image be provided by the OEM as part of each component material delivery to the government. The imagery would establish an initial database for comparative analysis. These images and associated configuration documents are used as a reference before a MRB ever goes into service, to ensure compliance with drawings and specifications upon initial delivery. If an incident were to ever happen with a MRB after installation, these images and files could always be referenced. In order to perform any type of image comparisons, sustainment images would be captured for comparison with the baseline or previous sustainment image. Any comparison of a baseline image to a sustainment image today would require the visual interpretation of an engineer or experienced maintainer. Unfortunately, this method of relying on image comparison may be negatively impacted by poor focus, as well as inexperience or subjectivity of the person performing oversight. Thus, it is recommended that one of the technologies explored in this document be used to generate baseline digital maps to improve analysis and comparison of MRBs during the inspection processes.

c. *Sustainment Digital Imagery*

One of the major changes recommended through analysis for the acquisition and sustainment process is to integrate a digital mapping and software comparison capability into the component inspection processes used in the sustainment phase of the MRB acquisition life cycle. Using technology to generate better inspection methods with improved detection, storing a digital map, and using software tools to quantify changes over time, the defense industry can realize cost avoidance opportunities and take measures to further eliminate faults leading to component failures before occurrence. After a baseline digital map is generated and stored, it can then be compared to new digital maps created during maintenance repair and overhaul activities. Our analysis supports considering the use of shearography or thermography as an inspection method for use during MRB sustainment activities.

d. Software Tools

The research conducted for this document did not go into any detail concerning the use of, and acquisition of, a software tool that could be used to analyze and/or compare digital images. However, the advance of technology over the last decade has allowed for a multitude of software analytic tools that are available in private industry. Such an example would be the facial recognition tools used in airports around the world. Software tools such as this allow for an evaluation of a captured image in reference to a baseline image. Thus, it is reasonable to assume that a software tool could either be acquired and/or developed or adapted from an industry technology that already exists.

2. Potential Areas for Further Research

Identification of software tools that could be used for analysis and comparison as follows:

- integrating automated software tools to enable AI analysis for complete integration with the digital enterprise
- incorporating baseline digital mapping with CAD drawing during the DD250 gain to inventory process as a means to verify quality assurance
- explore recommendations applied to other components to assist in life cycle management

3. Conclusion

Not only is it time to renew the current inspection processes used on Black Hawk MRBs that date back 4 decades, the Black Hawk sustainment community also recognizes a change is needed in order to improve cost. This is evidenced as a comment from the item manager, material release point notes within the I2LOG and LMP database, which identifies cost savings opportunity by avoiding manual labor cost associated with strip and rebuild overhaul activity. The statement regarding the cost of overhauling a blade twice to achieve the same operating time as purchasing a new blade identifies additional opportunity for savings—through use of improved inspection processes to reduce the

MTBRRDR and premature divestiture. The complete and direct quote regarding sustainment cost avoidance from the database item manager states:

> 7 July 2021, The New IDIQ for M&O Repair quantity of min120/max720 for the CAT IV Repair Program for the Legacy Blade has been cancelled as of 30 June 21. This a TOP 25 Readiness Driver. This action was being initiated to maintain the CAT IV repair program with the Sikorsky but has since been discussed and now needs to be canceled due to MEL Price being $119,404.23 and the Strip & Rebuild proposed cost on current PRON ranges from $136K to $174K as well as the decrease in AMD 50.79 as well as current SOH-293 BO's-0. This buy was needed so that we could continue to have a steady flow of assets to support the high AMD however, taking into account the number of hrs (average ~3,000 hrs) on Blades going into S&R, and if the average Blade lasts~6,000hrs, that means we would be paying approximately more than twice ($136,000 x 2 = $272,000) vs. new spares cost ($183,698.82). Mr. Muniz received approval from upper management within ALC which is allowing us to cancel this M&O Repair effort. ("I2LOG Material Release Point Notes," 2021)

In summary, this research detailed the aspects of the Black Hawk MRB and the associated life cycle processes. The primary goal of this research was to answer the three research questions:

1. Could digitally mapping MRBs provide a decision-making template to assist in evaluating component integrity to design specification?

   Answer: Yes, with a caveat of allowing a computer-aided system to analyze and correlate the initial component data from the OEM.

2. Are the benefits of digitally mapping MRBs throughout the component life cycle quantifiable?

   Answer: Yes, the benefits are appreciably quantifiable—based on cost savings opportunity examples and component reliability improvements gained from early defect detection and improving component QA processes. Also efficiencies gained by new technology infusion and digital imagery comparisons for structural anomalies revealed over time through use of automated software. The mapped data captured and compared during sustainment would feed product improvement initiatives and OEM component designs during next generation development and manufacturing improvement initiatives.

3. Do past and present MRB inspection methods and component documentation procedures still provide the best sustainment for the Army as we advance further into a growing digital environment and prepare for future conflicts?

   Answer: No, based on analysis, the Army has not taken a leap forward in fully digitizing or automating component inspection processes to document material condition. A lack of digital mapping limits opportunity for AI integration, subjecting components to cycles of inspections without correlation to previous or future inspections, and remaining subject to human inaccuracies that negatively impact component reliability.

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