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Mechanical Diagnosis and Prognosis of Military Aircraft: Integration of Wear, Vibration Time-Frequency Analysis and Temperature into Diagnosis Algorithms

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Abstract

In critical conditions, gears operate with insufficient lubrication and efforts are made to improve the life of these gears against wear. A local gear-tooth defect such as a fatigue crack, pit, or chip weakens a tooth and causes transient events in the system. The magnitude and duration of these events depend mainly upon the severity of the defect and the contact ratio of the gear pair. If the tooth fault severity is small and the contact ratio is high, the resulting transient may not show distinctively in the vibration signal; in such cases, a combination of vibration signals, time-frequency domain analysis, temperature, and other signals can be combined to reveal such events. This study presents a combined signal method for gear tooth failure prediction within the Tail Rotor Gearbox of an AH-64 helicopter under poor lubrication. From the investigation to date, a preliminary model of gear tooth failure resulting from a loss of lubricant has been fabricated. The present experiment will seek to more thoroughly quantify the present observations, and shall be analyzed further in future reports.

Keywords: diagnosis, prognosis, vibration, wear, temperature.

I. Introduction

One of the most expensive and time consuming tasks relating to Condition Based Maintenance (CBM) involves testing of mechanical components. This paper specifically addresses a rotorcraft tail gearbox testing at the University of South Carolina (USC) CBM test facilities. Furthermore, the CBM testing approach is discussed. The goal of testing is to identify the root causes of components' failure, failure modes, and the identification of ways to improve

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serviceability of aircraft components. Components' testing is carried out on used but serviceable components or on components with intentionally seeded faults.

As part of this effort, USC and the United States Army have identified the type of components to be tested based on their return value within a short time for implementation of CBM. The data was obtained over 35,000 flight hours and include 145 million data records from UH-60A, UH-60L, AH-64A, AH-64D, and CH-47D aircrafts. As an example, some of the chosen components that were tested at USC test facility include tail drive-train, Auxiliary Power Unit (APU) clutch, hanger bearings, main rotor swash-plate assembly and gear boxes discussed further. Monitoring of these components has already allowed the Army to eliminate the APU clutch vibration check and the special inspection on the main rotor swash-plate. In addition, it has allowed for the increase in Time Between Overhauls (TBO) for the hanger bearings, and time for the APU mount inspection. This resulted in a 5.2% increase in aircraft readiness and an annual savings of \$9.3M. Including additional components into CBM will allow for further increases in aircraft availability and annual cost savings.

The Army developed Modern Signal Processing Unit (MSPU) (vibration data acquisition and signal-processing equipment for the health monitoring of critical mechanical components) grew out of the Vibration Management Enhancement Program (VMEP) and is currently in use on a significant part of the Army helicopter fleet including AH-64, UH-60, and CH-47. The MSPU acquires data and calculates the condition indicators (CIs) used to determine the health of the drive system mechanical components. The next generation of the MSPU system will be utilized for developing and demonstrating advanced diagnostic capabilities for this technological area.

I.1. Background

Since 1998 the University of South Carolina and the South Carolina Army National Guard (SCARNG) have participated in a number of important projects that were directed at reducing the Army aviation costs (Abdel Bayoumi et al, 2008) through improved logistics technology, better data management and prompt decision making. This modern aviation maintenance transformation produces higher operational readiness using fewer, more capable resources, provides commanders with relevant maintenance-based readiness information at every level, and shifts the paradigm from preventative and reactive practices to proactive analytical maintenance processes, now commonly referred to as Condition-Based Maintenance. The benefits of these technologies have already been proven for helicopters on combat missions, training, and maintenance flight conditions.

The transition to CBM requires a collaborative effort on a massive scale and is contingent on identifying and incorporating enhanced and emerging technologies into existing and future aviation systems. This requires new tools, test equipment, sensors, and embedded on-board diagnosis systems.

The University of South Carolina has supported the U.S. Army by conducting research to support timely and cost-effective aircraft maintenance program enhancements. Research emphasis has been to collect and analyze data and to formulate requirements assisting in the transition toward Condition-Based Maintenance for the U.S. Armed Forces.

The research program at USC seeks to deliver results which directly contribute to CBM efforts and objectives as: link and integrate maintenance management data with onboard sensor data with test metrics and to quantify the importance of each data field relative to CBM; understand the physics and the root causes of faults of components or systems; explore the development of models for early detection of faults; develop models to predict remaining life of components and systems.

I.2. CBM Roadmap

As the growth and awareness of CBM develop, many ideas and technologies have arisen in efforts to improve CBM. There is need for a standardized methodology and roadmap for currently implemented military rotorcraft CBM to reach its full potential. In conjunction with the South Carolina Army National Guard, the University of South Carolina has the resources and channels to develop a roadmap to investigate the transformation of CBM. The activities of USC are being performed as a joint industry, academic, and government team.

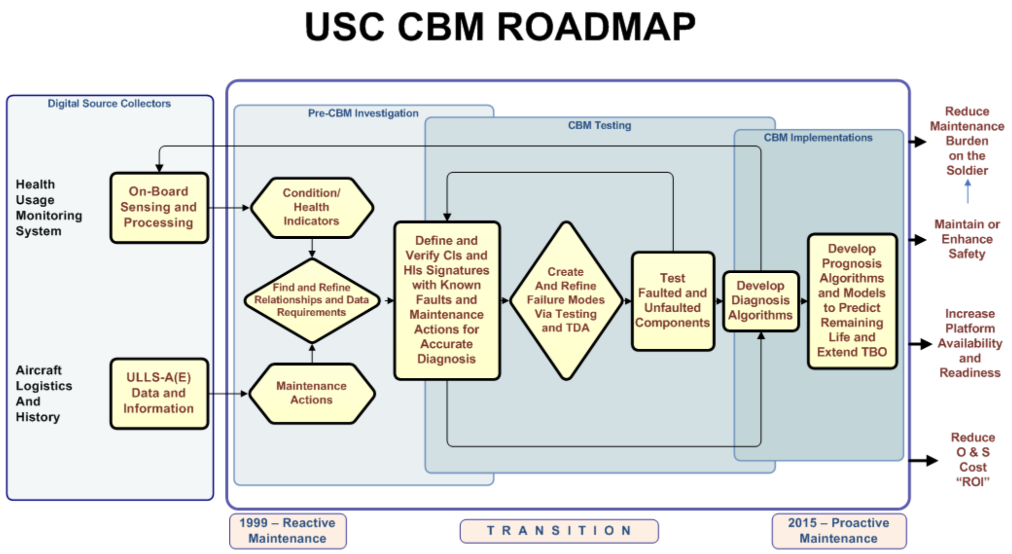


Fig. 1. The procedural roadmap currently being implemented by the USC CBM research program.

The proposed roadmap (Fig. 1) consists of three phases: initial investigation, component and system testing and the implementation of a fully-capable CBM system. This roadmap is driven by the currently available digital source collectors, which through integration and linking will direct the needs of laboratory testing. The results of this self-refining process will ultimately lead to the development of diagnosis and prognosis algorithms which will facilitate proactive CBM practices.

II. USC Test Facilities and Collaborations

USC leverages its eight years of active research, knowledge and expertise in vibration diagnostic development and the experience from previous CI development to lead the team in the drive systems/mechanical components technology area. The Condition-Based Maintenance Center at the University of South Carolina is one of the key players on the US Army CBM team. USC has focused on defining and developing a long-term roadmap of methodologies and processes that reinforce CBM activities and objectives. They are providing critical input for the path ahead as the U.S. Army moves towards CBM. State-of-the-art indoor helicopter test stands have been designed and built and are being used to test rotating components.

The purpose of such testing is to obtain measurements and data relative to the root causes of failure. This information is critical in moving toward Condition-Based Maintenance. The test stands shown in Figures 2 and 3 are capable of testing AH-64 drive train components (bearings, gearboxes, swash plates, oil coolers, and shafts). This stand is also capable of handling shaft misalignment requirements while remaining safe. Other stands at USC include an AH-64 hydraulic pump stand and an AH-64 main rotor swash-plate bearing assembly stand.

Fig. 2. USC Tail Rotor Drive Train (TRDT) test stand.

All test stands utilize several data acquisition systems, including current in-flight monitoring systems such as MSPU and IMD-HUMS, as well as a specialized laboratory data acquisition system capable of recording torque, speed, temperature, vibration, and acoustic emission. All test stands are controlled based on monitored data measures of torque, speed, and temperature, which are collected throughout the experiment. All vibration and acoustic emission data is collected as needed for the experiment. All test stand data files are migrated to a high-speed secure in-house file server with 2-terabyte storage capacity that is also ready to be accessed by Army personnel.

Fig. 3. USC Main-Rotor Swash-plate (MRSP) assembly test stand.

The TRDT test stands are designed to be flexible and practical for multiple purposes, while facilitating the ability to scientifically understand and interrogate the actual condition of components as they relate to TAMMS-A inspection, vibration signals, health and usage monitoring systems output, and other data sources. This data is needed for the development of comprehensive and accurate diagnosis algorithms and prognosis models. The testing capabilities are structured to test new and existing drive train components of military and civilian aircraft; with particular emphasis on AH-64, ARH-70, CH 47 and UH-60. Testing aircraft components will also support data requirements necessary for accurate diagnosis and proper maintenance of aging aircraft.

The specific test facilities, other research facilities, safety considerations, and research collaborations are described as follows:

TRDT Test Stand Specifications, Requirements and Features

The test stand emulates tail rotor drive train system from the main gearbox tail rotor takeoff to the tail rotor swash-plate assembly. All drive train parts on the test stand are actual aircraft hardware. The test stand was designed to handle shafts installed at the maximum allowed misalignment of over 2.0 degrees and balanced to the maximum allowed imbalance. The test stand mounting structure, instrumentation and data acquisition systems and schemes are in accordance with military standards. The test stand configuration, geometry and speed, and loading capabilities emulate airframe loads and flight regimes. The test stand was designed and built to accommodate the use of multiple Health and Usage Monitoring Systems (HUMS).

MRSP Test Stand Specifications, Requirements and Features

The swash-plate test stands were designed based on loading requirements and the shapes and sizes of the AH-64, UH-60 & CH-47 swash plates. The test stand is driven by an electric 50 hp A/C motor. This motor normally has an operating rpm of 1750, but by using an existing variable A/C vector drive the rpm is adjustable. These motors, when operating under their normal operating rpm, act as constant hp motors which will provide around 147 lb-ft of torque. If in the future motor torque is needed the motor may be run at operating speeds and have the rpm reduced through a gear reduction. As much as 908 lb-ft of torque can be obtained.

The drive motor provides the power and speed up through the center of the stand via a shaft; from here the shaft transmits power to a plate. In addition to transmitting the power, this plate provides a mounting place that accepts the scissors and the pitch links mounts, while supporting the loads of both. This plate will always run horizontally therefore provided a consistent plane in which the upper pitch link ends will rotate. The lower ends of the pitch links will attach to the non-rotating portion of the swash plate bearing which will be attached to the loading structure through its mounting holes.

Next, the loading structure is supported beneath the main rotor swash plate bearing mount table and a hydraulic cylinder applies the loading to the table mount which loads the pitch links. The loading cylinder is controlled via a highly accurate, electronically controlled constant pressure, valve. Each of the pitch links are instrumented with strain gauges for actual load monitoring. All strain gauge signals are amplified and passed through a slip ring before being recorded. By directly monitoring the pitch link loads, while precisely controlling our load an accurate reproduction of the loading is capable. This all occurs while rotating a portion of the swash-plate bearing at the specified operating speeds relative to the non-rotating portion of the swash plate bearing. This stand is capable of rotating from ~50 to ~ 656 rpm.

II.1. Other Capabilities Available at USC

The other capabilities available at USC to support the CBM research include: other data acquisition systems, modeling and simulation capabilities/software, state-of-the-art-metrology and measurement facility, tribology and lubricant analysis equipment, vision and imaging equipment, materials preparation and characterization equipment, and manufacturing and fabrication machines.

II.2. USC Test Stands Safety Considerations

All test stands are enclosed in a single, safe and secure area. Safety, hazards, security, and fire equipment are inspected and approved by both the USC Safety and Risk Management and the USC Fire Department. The safety features of all USC test stands consist of physical barriers around each stand to prevent any debris from reaching personnel near the testing area if breakage occurs during testing. Access near the testing area is prohibited during actual testing. Each test stand is featured with an emergency stop button to disable the test stand in the event the operator determines there is an unsafe/emergency condition.

II.3. Intelligent Automation Corporation

Intelligent Automation Corporation (IAC) is a machinery diagnostics company with a unique blend of research, systems engineering, manufacturing, and field support expertise. IAC proposes to leverage their extensive experience in drive train monitoring systems for Army and commercial helicopters to provide a system that can detect rotorcraft drive system faults with a high degree of accuracy. IAC proposes their recently developed SuperHUMS (IAC-1239, Fig. 4) system for this application. The IAC SuperHUMS system is an advance Health and Usage Monitoring System (HUMS) featuring state of the art field programmable gate array technologies.

The FPGA architecture is optimized for performing filtering, FFT, and other convolution functions that are the core of vibration related fault monitoring. With reduced software overhead, SuperHUMS can handle a wide variety of diagnostics. In addition to the FPGA, included with the system are three general purpose CPUs and high speed vibration input channels (96 kHz bandwidth) as well as up to 48 general purpose analog inputs that can be sampled up to 125kHz. The SuperHUMS system has the capability to host diagnostics algorithms developed by Boeing. IAC's diagnostics technologies that include existing diagnostic algorithms and neural network based anomaly detection techniques will enable the program goals by providing a high rate of automatic detection of critical mechanical component failures leading to reduced inspections, maintenance, and MTBRs.

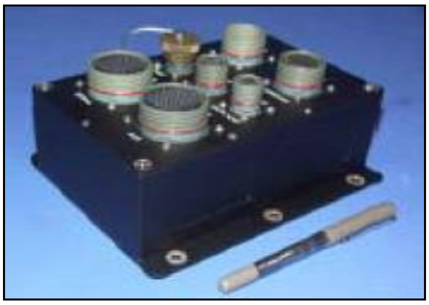


Fig. 4. IAC SuperHUMS (IAC-1239).

II.4. The South Carolina Army National Guard

SCARNG has been in the forefront of the VMEP development for several years. SCARNG currently has 16 AH-64A equipped with the VMEP system. With coordination from the U.S. Army AED, SCARNG will provide aircraft access for condition indicator demonstration. At the conclusion of the test stand testing and the CI enhancement, the VMEP/MSPU system on selected aircraft will be modified through the IAC database setup tool to incorporate enhancements to the vibration condition indicators. Data downloaded to the aircraft will be used to demonstrate effectiveness of the enhanced CIs on the ground station.

II.5. United States Army Aviation Engineering Directorate (AED)

The U.S. Army AED will provide the AH-64 drive system faulty components and seeded fault components for testing in the test rig at USC. Test plan and diagnostics enhancement approaches to be developed on the test rig will be closely coordinated with AED. AED will provide the Air Worthiness Release (AWR) required for incorporating and testing the diagnostics enhancements on selected aircraft at SCARNG.

III. CBM Test and Diagnostics Approach

A schematic of the CBM test and diagnosis procedure and its impact on achieving the CBM objectives are schematically shown in Figure 5. The procedures used for testing the mapped components (Abdel Bayoumi et al, 2008c) using the CBM research facility are described further.

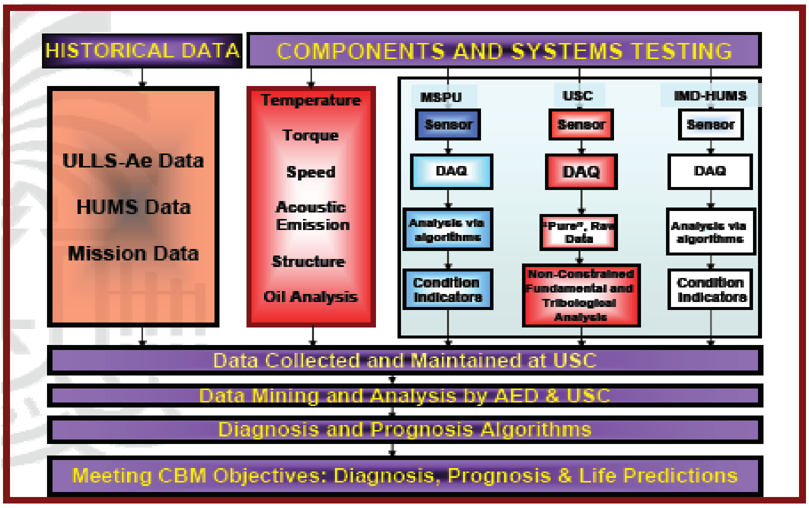


Fig. 5. CBM testing and its impact.

III.1. Test Preparation

USC generates the test plan and diagnostics enhancement approaches that are developed on the test rig, which are coordinated with AED. IAC and USC identify the instrumentation requirements and signal acquisition for the test stands at USC. The IAC and USC team also develop advanced diagnostics algorithms. IAC prepares a MSPU setup for the testing at USC, drawing on previous experience and technical support from IAC.

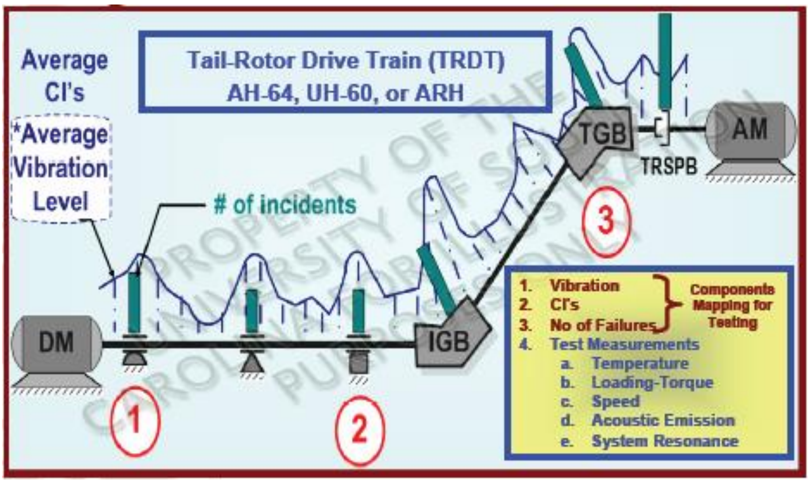


Fig. 6. Integration of test measurements with historical ULLS-A(E) and HUMS data to shape the future in achieving CBM objectives.

III.2. Seeded Fault Component Testing

USC conducts the test at their test stand with IAC and AED support. USC collects all instrumentation data. AED makes arrangements for post test teardown and inspection of the components. IAC supplies the MSPU system for testing. A schematic of integration of test measurements with historical data (Abdel Bayoumi et al, 2008a, b) is depicted in Figure 6.

The advanced diagnostics effort utilizes previous CI's developed in conjunction with dynamic component testing. These components have known faults as well as components with seeded faults to correlate, validate, and enhance the CIs toward their future use on the Apache aircraft. The program acquires aircraft dynamic components with known faults. These components are run on a test stand and the progression of failure is monitored until a failure or near failure condition. Next, these components undergo a formal inspection / teardown in order to correlate back to the findings from their testing. Newly developed CIs are then implemented on aircraft to further enhance their development and as a threshold validation between aircraft and test stand levels. The focus of the proposed diagnostics solution is to minimize missed and late detections while maintaining an acceptable false alarm rate. Both make use of the substantial amount of data that has been collected at the University of South Carolina using the IAC VMEP/MSPU system as well as the TAMMS-A Data of the same aircraft.

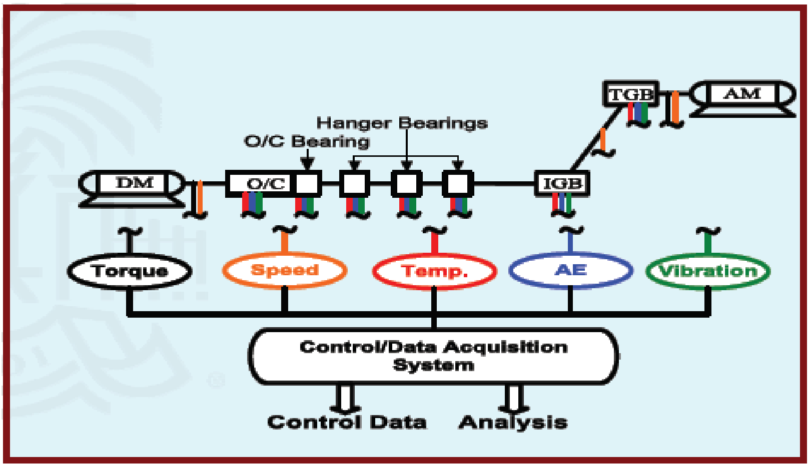


Fig. 7. Schematic of data acquisition systems and data collected.

III.3. Data Acquisition

While testing using TRDT test stand, all measured data (vibration, speed, load, temperature, etc.) are digitally acquired, warehoused and analyzed. It is possible to test multiple aircraft components simultaneously. The input speeds and loading are variable up to 120% of flight conditions (input speeds from 0 to 5000 rpm and loading from 0 to 1300 ft-lbs).

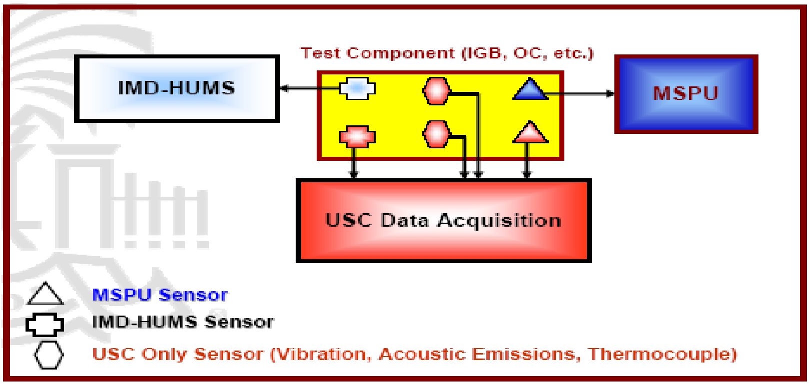
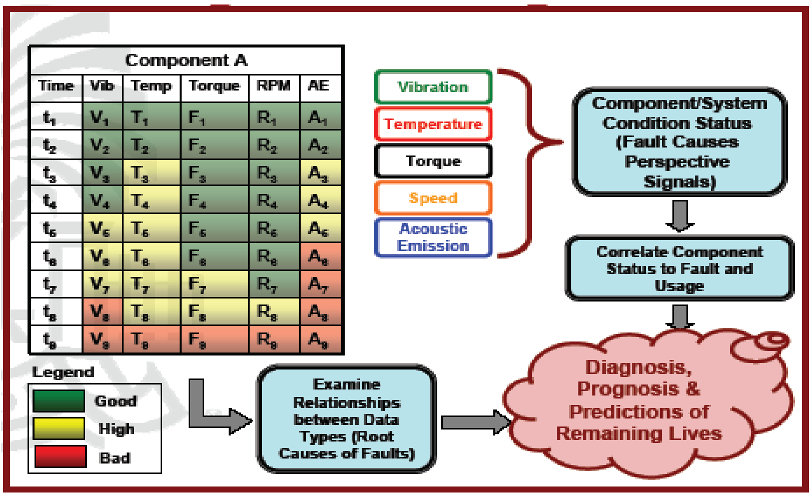


Fig. 8. Data acquisition strategy.

Safety regulations and Safeguards are implemented in accordance with both the USC and the U.S. Army rules and standards. The data acquisition characteristics and methods include: rotational speed in RPM, torque, vibration, temperature, acoustic emissions, and foreign particles per volume of oil. A simplified schematic of the Data Acquisition system and schemes including the control systems and components monitored is shown in Figure 7. For each test, the test data measured using the USC data acquisition system is compared with that obtained using IMD-HUMS and MSPU, which is shown in Figure 8.



Component A

Time	Vib	Temp	Torque	RPM	AE
t_1	🟩 V_1	🟩 T_1	🟩 F_1	🟩 R_1	🟩 A_1
t_2	🟩 V_2	🟩 T_2	🟩 F_2	🟩 R_2	🟩 A_2
t_3	🟩 V_3	🟨 T_3	🟩 F_3	🟩 R_3	🟨 A_3
t_4	🟩 V_4	🟨 T_4	🟩 F_4	🟩 R_4	🟨 A_4
t_5	🟨 V_5	🟨 T_5	🟩 F_5	🟩 R_5	🟨 A_5
t_6	🟨 V_6	🟨 T_6	🟩 F_6	🟩 R_6	🟥 A_6
t_7	🟨 V_7	🟨 T_7	🟨 F_7	🟩 R_7	🟥 A_7
t_8	🟥 V_8	🟨 T_8	🟨 F_8	🟨 R_8	🟥 A_8
t_9	🟥 V_9	🟥 T_9	🟥 F_9	🟥 R_9	🟥 A_9

Legend
🟩 Good
🟨 High
🟥 Bad

Fig. 9. Development of diagnosis and prognosis algorithms.

III.4. Validation of Diagnostics

USC performs data analysis and algorithm development to examine CIs for proper threshold levels and development of additional CIs. This is schematically shown in Figure 9. USC utilizes an automated data mining approach to automatically determine optimized CI threshold settings from both normal and validated fault data. An automated data mining approach is also used to automatically determine optimized prognosis algorithms and, in turn develops models for components life predictions. IAC provides technical support for validation.

An automated data mining approach has been developed. The approach automatically determines optimized threshold settings using CIs developed from both normal and validated fault data. The faulted CI data is used to determine detection performance while normal data is used to determine false alarm rates. In addition, the efficacy of all CIs for detection of a given fault will be assessed. Different CIs for a given fault have different false alarm performance due simply to different processing noise. Integration of complementary CIs improves detection performance while reducing false alarms. The CIs tend to be complimentary in detecting faults while falsely alarming in different places. Trending (slope estimate) of CIs are included in the detection. IAC investigates and includes trend analysis to improve detection performance in the Apache HUMS.

IV. Testing Results

One of the latest test articles at the test facility was a Tail Rotor Gearbox (TGB) (Fig. 10) that was tested for durability under critical lubrication conditions. That is a bevel spiral tooth gear, having a 22:57 transmission ratio, operating at approximately 3700 rpm input shaft speed.

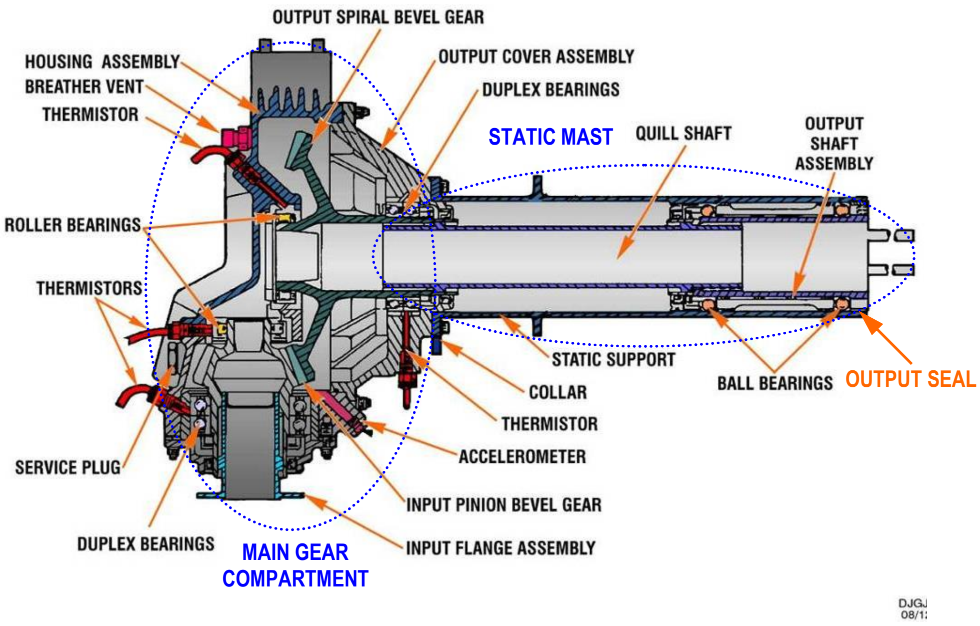


Fig. 10. AH-64 Tail Rotor Gearbox cross section.

The reasoning behind the experiment was that output seal (Fig. 10) on the static mast of the gearbox often starts leaking grease and it can not be replaced without servicing the static mast. Also the procedure requires grounding of the helicopter and fixing the seal immediately after the leak is detected. It cannot be accomplished without removing the entire gearbox and tail swash-plate, which is a time consuming process and keeps helicopter grounded in case of a mission. So the intent was to test performance and durability of the gearbox in case it is kept as is with the output seal leaking and see if it can last 250 hours till its scheduled maintenance date or end of a mission.

The experiment was set up so the gearbox would gradually leak all of its grease during the first 150 hours of operation, resulting in accelerated wear, measured vibrations increase and deceiving temperature drop due to heat transferring medium loss and heat localization.

When the gearbox is fully serviced, the grease acts as a heat sink/mediating medium that helps to efficiently dissipate localized heat generated at the gear-mesh and initially as the lubricant in the friction pair. Also it is the transfer medium that distributes heat to thermocouples installed inside the gearbox (thermistors that are originally installed on the gearbox were replaced by thermocouples at the USC test facility). That is the way a gearbox is designed and expected to operate. When the lubricant is lost, it leaves air as the mediator, leading to heat localization and thermal gradient/bias that shows up as a misleading lower temperature inside the gearbox.

Empirical-hypothetical vibration, temperature, and wear propagation is depicted in figure 11. In addition to automated sensor data logging, optical tooth wear observations were made manually with digital borescope between the test runs. Testing was concluded after significant teeth deterioration and tooth fracture.

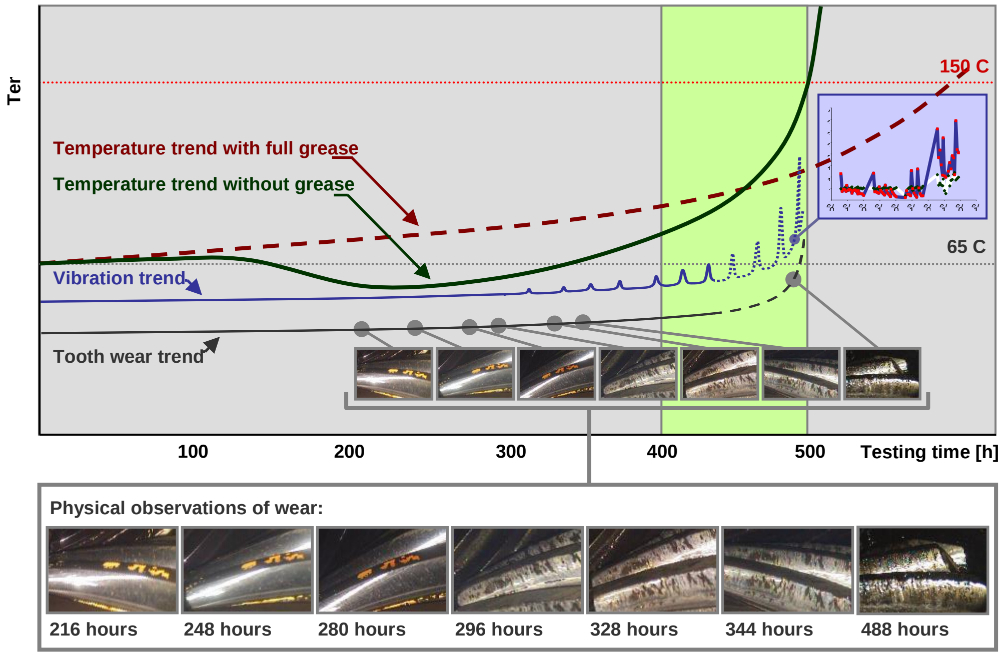


Fig. 11. A hypothetical scheme to relate temperature, vibration, and wear.

Testing fully proved its expectations by providing valuable MSPU calibration data and supporting the importance/necessity of component testing for CBM program development. This conclusion is based on the discovery that some thresholds for CIs, that are most informative and critical in gearbox diagnosis, were set too low in attempt to minimize false alarm rates due to an absence of data of failure propagation to that extent. For example, Sideband Index (sum of largest gear-mesh frequency sidebands divided by the number of sidebands) (vibrations acceleration level was set well above 4 g (Fig. 12)) or Diagnostic Algorithm 1 (RMS of Signal Average) did not show warning signs due to inadequate diagnostic threshold levels.

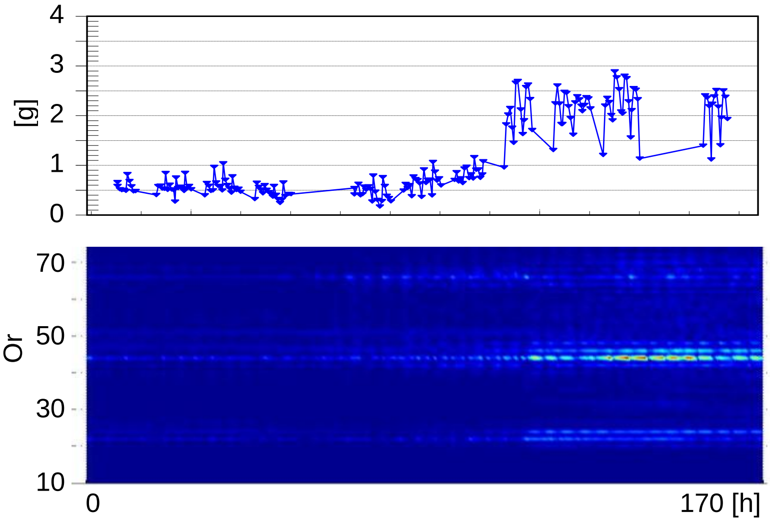


Fig. 12. TGB Sideband Index CI and vibration order trends over time.

Similarly it was shown that temperature is a better indicator of an impending problem in case of poor lubrication (Fig. 13), showing clear deviations from nominal operation temperature, while vibration levels and tooth wear remained relatively low in order to cause concern.

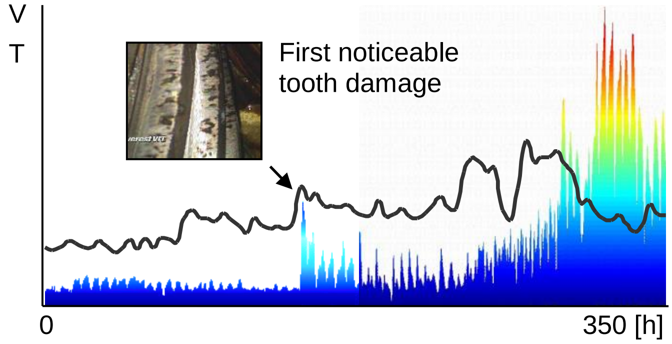


Fig. 13. Maximum vibration level over measured frequency band and temperature plots over time.

Such findings give support for MSPU modernization by additional sensing capabilities and data fusion implementation in order to enable earlier identification and diagnosis of an impending fault.

Data, feature and information level fusion techniques include voting, weighted voting, Bayesian inference, Dempster-Shafer theory, neural networks, fuzzy logic (Vachtsevanos, G., et al, 2007).

Voting and weighted voting decision fusion techniques can be implemented by assigning weights to sensors/condition indicators based on a priori knowledge of their accuracy/efficiency at detecting a certain fault or their correlation.

Some sensors can be ignored or assigned a low credibility based on their performance in time or fault being diagnosed. Also the sum of the weights must equal 1. If all weights are set equal, weighted voting is reduced to voting (David, L., Hall and James Llinas, 2001).

Basically each sensor, *i*, outputs a binary vector, x_i, with *n* binary condition indicator values corresponding to given faults. The classification vector, $x_{i,}$ from sensor *i* becomes the i^{th} row of the weighting matrix *A*. Each row of the matrix is weighted using the a priori assumption of the sensor liability W_i. Subsequently the elements of the array are summed along each column:

$$D(j) = \sum_{i=1}^{m} W_i(t) A[i, j], \qquad (1)$$

where *D*(*j*) is a fused decision on fault *n*, *m* – number of sensors, *W* – weighting factor, *t* – time.

This way practical approach to data fusion can be taken without the need of initial a priori probabilities of a fault or conditional probabilities of a sensor identifying a fault that are needed for Bayesian inference or Dempster-Shafer methods and initially might be unavailable.

Conclusions

The transition of the U.S. Army rotorcraft fleet maintenance practices to CBM requires a collaborative joint industry, academic, and government team effort.

When critical operation conditions of a component are not estimated in initial design process of the component and system, it can lead to misleading sensor and diagnostic system readings.

Aircraft component durability testing is an essential tool in CBM program development, supplying necessary calibration data for condition monitoring and diagnostic systems, giving insights to design flaws and improvement possibilities.

Multi-sensor implementation and data fusion give an opportunity to enhance and accelerate impending problem diagnosis and CBM system development.

References

Abdel Bayoumi, Nicholas Goodman, Ronak Shah, Les Eisner, Lem Grant, Jonathan Keller, 2008a, "Conditioned-Based Maintenance at USC - Part I: Integration of Maintenance Management Systems and Health Monitoring Systems through Historical Data Investigation", in Proceedings of the AHS International Specialists’ Meeting on Condition Based Maintenance, Huntsville, AL, 12-13 Feb 2008.

Abdel Bayoumi, Nicholas Goodman, Ronak Shah, Les Eisner, Lem Grant, Jonathan Keller, 2008b, "Conditioned-Based Maintenance at USC - Part II: Implementation of CBM through the Application of Data Source Integration", in Proceedings of the AHS International Specialists' Meeting on Condition Based Maintenance, Huntsville, AL, 12-13 Feb 2008.

Abdel Bayoumi, Nicholas Goodman, Ronak Shah, Trevor Roebuck, Andrew Jarvie, Les Eisner, Lem Grant, Jonathan Keller, 2008c, "Conditioned-Based Maintenance at USC - Part III: Aircraft Components Mapping and Testing for CBM", in Proceedings of the AHS International Specialists' Meeting on Condition Based Maintenance, Huntsville, AL, 12-13 Feb 2008.

Abdel Bayoumi, Nicholas Goodman, Ronak Shah, Les Eisner, Lem Grant, Jonathan Keller, 2008d, "Conditioned-Based Maintenance at USC - Part IV: Examination and Cost-Benefit Analysis of the CBM Process", in Proceedings of the AHS International Specialists' Meeting on Condition Based Maintenance, Huntsville, AL, 12-13 Feb 2008.

Vachtsevanos, G., Lewis, F. L., Roemer, M. J., Hess, A., Wu, B., 2007, "Intelligent Fault Diagnosis and Prognosis for Engineering Systems", Wiley.

David, L., Hall and James Llinas, 2001, "Handbook of Multisensor Data Fusion", Boca Raton, FL: CRC Press.

Adler, Matthew, Eric Posner, 1999, "Rethinking Cost-Benefit Analysis," University of Chicago Law School, John M. Olin Law & Economics Working Paper No. 72.

Crews, Samuel T., 1991, "Helicopter Vibration and its Effect on Operating Costs and Maintenance Requirements," AMCOM, Huntsville, AL.

Giurgiutiu, V., Grant, L., Grabill, P., Wroblewski, D., 2000, "Helicopter Health Monitoring and Failure Prevention through Vibration Management Enhancement Program", Proceedings of the 54th Meeting of the Society for Machinery Failure Prevention Technology, May 1-4, 2004, Virginia Beach, VA, pp. 593-602.

Grabill, P., Grant, L., 1996, "Automated Vibration Management Program for the UH-60 Blackhawk", 52nd Annual Forum of the American Helicopter Society, Washington DC, June 4-6, 1996.

Milford, M. Alex, 1998, "HUMS Cost/Benefit Analysis Model: Benefit Element Report", Booz-Allen & Hamilton, Inc., DAL Conference, September 30, 1998, Seattle, WA.

Parker, M., 1997, "Mission Possible. Improving design and reducing costs at Boeing Helicopter", IIE Solutions, Vol. 29, Dec. 1997, pp. 20-24.