



# CBM@USC Project Portfolio

Director

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This document provides a brief overview of the Condition-Based Maintenance (CBM) related projects that the CBM Research Center at the University of South Carolina has i) been involved with and may continue, ii) currently on-going or iii) proposed for future needs by the defense or industry. The following is a short description of each project with a list of value-added/anticipated outcomes followed by its broad applicability to CBM.

Projects are grouped into the following five major areas:

1. Cost-Benefit Analysis and CBM performance indicator – **CBA**
2. Testing, sensing development and qualification for CBM – **TESTING**
3. Tribology (friction, wear, lubrication, surface studies, failure modes) – **TRIBOLOGY**
4. Smart Predictive System (diagnosis, prognosis and life prediction) – **PREDICTIVE TOOLS**
5. Natural Language Processing for better data collection and analysis – **NLP**

## **1. Cost-Benefit Analysis and CBM Performance Indicators (CBA):**

**Cost-benefit analysis is used to evaluate the value added to a system by implementing on-board sensing, HUMS and CBM methodologies.**

### **a. CBM Performance Indicator: Value Engineering Through Cost-Benefit Analysis:**

This project looks at the additional costs for CBM compared to other traditional maintenance processes. Value added is addressed by quantitative benefits like cost savings, qualitative benefits (such as sense of safety, performance) and time savings. The financial effectiveness of CBM implementation on aircrafts is examined by developing a generic cost-benefit analysis (CBA) model. The model would account and convert relevant aspects of costs and benefits into a single unit of measurement which is dollar value and determines the cost-benefit ratio. Possible outcomes include:

- understanding of users' perspective to safety and performance to understand the creation of incentives for Army personnel at all levels to adopt CBM
- a model for estimating qualitative benefits in terms of a dollar value, and estimation of amount of time saved
- integration of quantitative and qualitative benefits
- a model for measuring financial effectiveness of CBM implementation

This value model tool could be used by commercial and military groups looking to implement CBM practices to determine financial/engineering effectiveness.

*POC: Tanzina Zaman*

### **b. RIMFIRE Field Repairable T-700 Engines:**

This project involves utilizing RIMFIRE to determine a way to reduce field repairable T-700 engines from being sent to depot. A large portion of the engines found to be field repairable require only part replacement or benching/chamfering of airfoils. A checklist could be made for maintainers to quickly reference prior to sending engines to CCAD. For example, for airfoil erosion, the solution could be as simple as a card with a sample airfoil (to size) displaying green/yellow/red lengths that are acceptable (i.e. 15% chord reduction is green/good but 40% reduction is red/bad). Using this information, potential savings can be determined from implementing proposed changes. Possible benefits include:

- saving time and money by reducing the number of engines sent to depot
- increased engine and aircraft availability
- reduction in test flights due to engine replacement
- soldier and maintenance burden reduced
- operational support cost reduced

This methodology is being explored to other engines in the fleet.

*POC: Erin Ballentine*

### **c. Vibration Control Return on Investment for Apache AH-64D**

This project examines the benefits of implementing main rotor blade wedges on the AH-64D aircraft. The wedges are placed on the blades of the aircraft to reduce vibration, much like a fan blade balancing kit corrects wobble in ceiling fans. The analysis predicts the material and operational costs that will be avoided by using wedges instead of bending trim tabs (the current balancing method). Value-added benefits include:

- quicker, easier, and more accurate than bending trim tabs
- reduced maintenance time and required number of rotor smoothing events
- elimination of trim tab washout as a fault, leading to decreased blade demand
- lower vibration levels experienced in overall aircraft
- three of four CBM objectives are affected: the soldier and maintenance burden is reduced, operational support cost is reduced, and aircraft availability is increased
- 10-year return on investment between 9.8:1 and 23:1 for the current rate of flight and a range of projected peacetime flight hours

ROI can also be determined for implementation of wedges on other aircraft.

*POC: Erin Ballentine*

## **2. Testing, Sensing Development and Qualification for CBM (TESTING):**

**This area encapsulates USC's testing methodologies, test stands and associated component testing and sensor testing.**

### **a. AH-64 Tail Rotor Gearbox Study:**

This project involves component testing of the tail rotor gearbox under seeded fault conditions. The fault under examination was of the tail rotor gearbox leaking grease through its input and output seals. An experiment was designed to create a worst-case scenario for a leaking output seal on three different high-life gearboxes, which were to be run for 500 hours in a seeded fault condition. The test objective was to demonstrate that aircraft with leaking output seals could continue to operate until a scheduled phase maintenance. Although previously considered impossible, during the study it became evident that grease freely moves from the main gear compartment into the static mast. As a result, the output seal leaks caused lubricant starvation on the gear mesh surfaces, ultimately leading to catastrophic failures of the input gear teeth. The three gearboxes tested survived 490, 487, and 573 hours after fault seeding, and numerous vibration and thermal observations were recorded as the gearboxes approached failure. Value added includes:

- changed maintenance practices fleet-wide
- new output seal removal tool was designed by USC and is currently used in the field
- improved aircraft airworthiness
- reduced part costs, necessary downtime, and labor requirements

**b. Implementation of the Tail Rotor Swashplate on the Tail Rotor Drive Train Test Stand(AED):**

The tail rotor swashplate (TRSP) was added to the TRDT test stand to increase testing capabilities. To implement these changes, new components including the TRSP, spherical bearing, and hydraulic cylinders were added to the test stand to allow for swashplate testing. The test stand can replicate the loads that are normally experienced by the swashplate during flight. An additional benefit is that more sensors can be tested. For example, adding strain gauges to the pitch links creates the opportunity to verify the pitch link loads, and to also quantify the load experienced during regular aircraft operation.

*POC: Travis Edwards*

**c. Main Rotor Swashplate Test Stand (AED):**

This test stand is designed to test the main rotor swashplate for an Apache helicopter. The stand uses an electric motor to spin the swashplate at the actual speed of the helicopter. Hydraulic cylinders are used to input loading conditions seen during flight. Vibration data is collected and processed from the swashplate through the MSPU (Modernized Signal Processing Unit). Benefits include:

- can easily be modified to test other aircraft main rotor swashplates such as Blackhawk, Chinook, etc.
- allows for development of new CIs and refinement of existing CIs
- speed of drive motor is easily changed, so over speed testing can be conducted easily
- hydraulics can be used to apply large forces for overload testing

*POC: Thomas Hartmann*

**d. Advanced Vibration Sensing Radar (ADVISER) for Condition Monitoring of the AH-64 Tail Rotor Drive Train System (Honeywell):**

This project was to test Honeywell's ADVISER sensor and its potential diagnostic and prognostic capabilities. This was done using AH-64 tail rotor drive train components. The ADVISER is a non-contact sensor that uses a 24GHz Doppler radar to transmit RF energy to the targeted component and the RF energy is reflected back from the targeted surfaces and edges. The sensor measures the phase change between input and output signals caused by the target displacement. The ADVISER sensor has a wide field-of-view giving it the capability to monitor more than one component at a time. Benefits include:

- new non-contact sensor for CBM use
- platform independent
- reduction in the required number of sensors and consequently overall weight

*POC: Alex Cao*

**e. Rotor-Head Test Stand and CBM Analysis (pending proposal to Boeing):**

This pending project is a USC proposal to Boeing to support their effort to use a full-scale Rotor-Head Test Stand for the AH-64E main transmission (XMSN). Boeing proposes to use USC's capabilities to accomplish the following tasks:

- i. use the Tail Rotor Drive Train (TRDT) test stand to support the development of surface acoustic wave (SAW) torque sensor for tail rotor shafts
- ii. support the development of CI algorithms to detect failure of planetary stage gear and bearing
- iii. support interim power rating project
- iv. use the TRDT and Main Rotor Swashplate (MRSP) test stand to support the validation of Honeywell's miniature ADVISER sensor for HUMS integration
- v. use the TRDT and MRSP test stand to support the development and validation of MicroStrain's wireless module to measure strain on the main transmission

Potential project benefits include:

- rotor-Head Test Stand for CBM testing at USC
- development of new sensors and sensor systems for CBM use (SAW, ADVISER, MicroStrain wireless modules)
- interim power rating methodology for the ageing of drive train components under variable power loads
- CI algorithms to detect failures in planetary stage gears and bearings systems

*POC: Alex Cao*

**f. Dependence of Vibration Characteristics on Grease Service Levels in an Intermediate Gearbox:**

This project involves determining if a correlation exists between the grease service level and the vibration magnitude of the intermediate gearbox (IGB). To detect physical changes in helicopter components, condition indicators (CI) are calculated using various algorithms. However, there are limitations on the extent at which CIs can detect problems since each of these algorithms is targeted to a specific fault. Currently, no CI can directly detect grease loss in the IGB so the service level has to be checked every 25 flight hours by a maintainer. Potential outcomes could include:

- confirmation of current maintenance practices (for no correlation); thus strict grease level monitoring system is less crucial to the health of the helicopter
- potential increase accuracy of fault characterization (if correlation exists); variation in the grease level will have an effect on CIs

*POC: Travis Edwards*

#### **g. Improved Tail Rotor Tachometer Clearance (AED):**

This project's purpose was to evaluate a new tail rotor tachometer design for the AH-64D Modernized Signal Processing Unit (MSPU). The old tail rotor tachometer design for the MSPU required a gap between 0.022 and 0.024 inches. This very small gap was troublesome to maintain in the field for extended periods of time. Also, the current tachometer sensor has exhibited reliability problems just after installation, which may be related to its low tolerance gap requirement. A new tail rotor tachometer design would permit a larger gap, and hence increase its ease of use and reliability. Different tachometer designs were tested at two speed configurations on the test stand, FPG101 and FPG70. Value-added outcomes include:

- current tachometer design could be taken with a gap of 0.043 inches (nearly doubled the current limitation)
- new tachometer interrupter allowed surveys to be taken with a gap of 0.25 inches, which was the maximum allowable tolerance for testing

*POC: Travis Edwards*

#### **h. No-Load Test Stand:**

The no-load test stand is capable of being used as either a preliminary test bed for components before moving to the full-load test stand or reconfigured to accommodate other drive train systems. Currently, the no-load test stand is set up similarly to the tail rotor drive train test stand. The test stand is driven by a 5 horsepower motor and has no misalignment. When configured to be a UH-60 test stand, the tail rotor drive train output motor is turned 180° to accommodate a Blackhawk tail boom and the input motor is slid down the rails to be used on the drive train. This configuration allows the test stand to operate up to 150% of the operational power of the aircraft. Value added includes:

- allows for full speed testing of components without the added sensor noise from applying a torque load
- highly configurable for testing of a multitude of components across multiple rotor drive trains

*POC: Jacob McVay*

#### **i. Research and Development (R&D) Test Stand:**

Conceptually, the R&D test stand can be used as a preliminary or single component test stand much like the current configuration of the no-load test stand. In the past, single bearings have been tested, but the test stand could easily test items such as single gearboxes, hanger bearings, transmissions, etc. The R&D test stand is highly configurable allowing for various test configurations. The test stand is currently wired with power and sensor boxes to accept accelerometers and thermocouples and fed into a data acquisition system in a weatherproof enclosure. Value added includes:

- testing smaller components that don't require the power and strengths of the TRDT or no-load test stand
- testing components in a controlled instrumented environment

- lower testing costs
- educational component for students

The R&D test stand is academically supported and is also used for educational purposes as a learning tool for students.

*POC: Jacob McVay*

### **3. Tribology (friction, wear, lubrication, surface studies, failure modes) (TRIBOLOGY):**

**Tribology is the study of friction, lubrication and wear to improve understanding of a lubricant's behavior in aircraft.**

#### **a. Nano-lubricant Additives in AH-64 Intermediate Gearbox (NEI):**

This project in partnership with NEI aims to increase the performance of the intermediate gearbox. This is done by investigating and testing different nanoparticle additives in Mobile Aviation Gear Lubricant (AGL) as a potential improved lubricant in a proof-of-concept study. Lubricant leaks in drive-train gearboxes still remain a key issue and a common fault in the field. Nanofluids have proven to be efficient for heat transfer for better cooling purposes and extending the component's life by increasing the thermal and rheological properties of fluids. This is achieved through the incorporation of nanoparticle additives to boost thermal conductivity with maintaining a minimum impact as much as possible on viscosity. Thermal and vibration condition indicator (CI) characteristics from the gearbox were measured using rheometers and viscometers available in USC's chemical engineering facilities. Results showed benefits including:

- temperature of the gearbox containing nanofluid operated 20°F cooler than its counterpart AGL which had no nanoparticles
- nanoparticle additives with AGL can be used as a lubricant in gearboxes to improve performance (e.g. lower operating temperature) in other aircraft
- some vibration and CI responses from the nanofluid were less in magnitudes than those from the base AGL with no nanoparticles

This has led to a potential future collaboration with GasTOPS and South Carolina Army National Guard on debris analysis for lubricants.

*POC: Kareem Gouda*

#### **b. Implications of Simultaneous Mechanical and Thermal Loads on the Rheological Properties of the Grease in AH-64 Helicopter Gearboxes:**

This project deals with changes in the rheological properties of the grease used in the tail rotor and intermediate gearboxes of the Apache AH-64 helicopter when subjected to simultaneous mechanical and thermal loads within its operating temperature limits. It was observed that there is a significant reduction in apparent viscosity over the shear rate range tested. This reduction in apparent viscosity might lead to inadequate lubrication in contact regions between teeth thus accelerating tooth wear. To

verify if the change in properties was due to temperature alone, studies were conducted on grease samples heated in a convection oven at 195°F. Results showed that the effect was not solely due to temperature alone. However when simultaneous mechanical and thermal loads were applied, there was a dramatic change in the rheological properties of the grease. It was observed that the grease reaches a stable or a metastable state and thereafter it does not seem to have much change in apparent viscosity either with operating conditions or time. The grease in this stable or metastable state has significantly different rheological properties than the virgin grease. Value-added benefits include:

- increased knowledge of the rheological properties of grease used in gearboxes with regard to lubrication, temperature and performance
- integration of oil analysis within existing CBM infrastructure; strives to increase the overall efficiency of real-time health monitoring systems for wetted components

*POC: Jacob McVay*

#### **4. Smart Predictive System (Diagnosis, Prognosis and Life Predictions) (PREDICTIVE TOOLS):**

**The smart predictive system aims to fuse data from theoretical simulation models with empirical test stand data to develop diagnostic, prognostic, and life prediction algorithms.**

##### **a. Higher-Order Spectral (HOS) Analysis of Vibration Signals:**

This project involves using higher-order spectral analysis for diagnostics and characterization of vibration signals. Traditional linear spectral analysis techniques of the vibration signals, based on auto- and cross-power spectra, are common tools for diagnoses of rotating components. However, linear spectral analysis techniques are of limited performance in diagnostics when various spectral components interact with one another due to non-linear or parametric processes. In such a case, non-linear spectral analysis techniques (HOS analysis, also known as Polyspectral analysis) are recommended to accurately and completely characterize the vibration signals. HOS are frequency domain representations of higher-order correlation functions that investigate nonlinear dependency among signal components. Value-added benefits of HOS include:

- more robust and accurate diagnostic models for components in the aircraft
- yields additional information that can be used to gain more knowledge and get more accurate diagnostics than classical spectral analyses
- provide more information that describes the root cause of certain frequencies appearing in the vibration spectrum where classical spectral analysis is usually not sufficient

These Higher-Order Spectral techniques can be used on any aircraft's sensor data (of rotating components) to yield additional diagnostic information compared to traditional condition indicators.

*POC: Dr. Mohammed Hassan*

### **b. Planetary Gear Failure Algorithm Solution (pending proposal to Boeing)**

This pending project is a USC proposal to Boeing to provide a theoretical planetary gear failure algorithm solution. USC proposes to provide a theoretical framework relating planetary gear system inputs and outputs. The framework would consist of multi-component sub-assembly models that will be integrated into planetary gear failure detection techniques for the tail rotor drive idler gear within the AH-64E XMSN. This would allow prediction of planetary gear failures under a variety of simulated conditions. This will be accomplished through a variety of relevant simulation models (dynamic, thermal, stress etc.). USC will demonstrate the reliability and robustness of the simulation and modeling capability of the proposed algorithm solution by correlating the simulated response with condition indicators from test stand data. Potential project benefits include:

- integrated models and simulations for the prediction of future component condition or remaining life under expected conditions for a variety of failure conditions
- increased reliability of planetary gear components and affected systems
- more efficient and effective use of sensors for early detection of component failure
- CBM tool in the design of components

*POC: Dr. Josh Tarbutton*

### **c. Rotorcraft Predictive Maintenance (in partnership with IBM):**

This pending project in partnership with IBM is looking at using data mining techniques on aircraft maintenance data to extract useful relationships for CBM in building a smart predictive system. Data will be collected from different sources, such as ULLS-A (aircraft logbooks), HUMS (aircraft sensor data) and test stand data. Using IBM's Predictive Maintenance and Quality (PMQ) software, statistical predictive models will be built from the data fusion of these qualitative and quantitative data sources. Potential benefits include:

- predictive tools for remaining useful life at the aircraft and fleet level; dynamic prediction based on actual condition
- predictive tools for component failure; potential to extend time between overhaul
- causal factors to remaining useful life and component failure; correlation of maintenance actions to causal factors
- proactive planning of future maintenance schedules and actions

*POC: Alex Cao*

## **5. Natural Language Processing for Better Data Collection and Analysis (NLP):**

**Natural language processing is the process of converting natural human speech or writing (such as logbooks, reports, emails etc.) into a computer understandable form.**

**a. Information Extraction Methods for Latent Relationship Discovery (Pending SBIR Proposal for the Air Force):**

This project proposes identifying latent relationships between multiple data sources, that is links between entities and events that are not explicitly stated. In order to get a complete analysis of an entity or event, information from unrelated sources must be brought together and correlated. Manually identifying these entities is neither practical nor cost-efficient, so we turn to natural language processing (NLP) and machine processing for this task. NLP aids in the task of rendering structured and unstructured text into machine readable form that can be processed and analyzed by an information extraction system. Value-added benefits include:

- method for analyzing textual sources (e.g. maintenance records and logbooks) and extracting information that can be used in conjunction with HUMS data to meet CBM objectives
- analysis of extracted information from different types of CBM data to detect patterns and draw conclusions
- extracted entities and events from unstructured data sources may be used to populate a database for data mining efforts

Tools developed such as a named entity recognition system, relation extractor and overall information extraction system can be modified with little difficulty and used across data sources for various products and aircraft systems to meet individual needs.

*POC: Rhea McCaslin*

**b. V-22 Osprey Natural Language Processing (Boeing):**

This project is part of a general effort to apply natural language processing (NLP) techniques to improve reliability and reduce costs of V-22 aircraft. The program has three main objectives. First, research and develop methods to align maintenance actions, based on what was reported in the free-text fields with entries in the aircraft's technical manual. Second, trim the unwieldy technical manual of redundant entries, for which entries that are semantically similar but syntactically different needed to be recognized. Third, research the suitability of current ontology technologies for creation of a maintenance "reasoner" knowledge base. Value-added results include:

- creation of a new text pre-processor specific to maintenance records, that improves the performance of baseline NLP part-of-speech tagging and entity extraction methods
- program to identify similar text entries amongst large textual data stores and categorize them by degree of differentiation
- survey of ontology technology for use in context of mechanical maintenance environment

The methods and algorithms developed specifically for maintenance records can be applied to other aircraft text data (i.e. logbook) to extract useful information and find patterns.

*POC: Huston Bokinsky*