Component Testing for the Smart Predictive System

Alex Cao
caoa@sc.edu
Research Engineer
Mechanical Engineering
University of South Carolina
Columbia, SC, USA

Joshua Tarbutton
jat@sc.edu
Assistant Professor
Mechanical Engineering
University of South Carolina
Columbia, SC, USA

Rhea McCaslin
mccaslir@email.sc.edu
Research Assistant
Computer Science
University of South Carolina
Columbia, SC, USA

Erin Ballentine
ballente@email.sc.edu
Research Assistant
Mechanical Engineering
University of South Carolina
Columbia, SC, USA

Lester Eisner
lester.eisner@us.army.mil
Major General
Office of the Adjutant General
South Carolina Army National Guard
Columbia, SC, USA

Abdel-Moez Bayoumi
bayoumi@sc.edu
Professor
Mechanical Engineering
University of South Carolina
Columbia, SC, USA

ABSTRACT

An important part of Condition-Based Maintenance (CBM) is the component testing of faulted articles. The University of South Carolina's CBM test facilities have accumulated thousands of hours of component testing of faulted articles and as a result, gained invaluable testing experience. Faulted articles can fall into two categories: seeded and natural faults. Each has their benefits and drawbacks. Component testing of faulted articles can serve multiple purposes such as verifying or improving existing condition indicators or creating new ones. Faulted articles undergo a tear down analysis after testing in order to determine the actual condition of components. Three case studies are presented showing seeded fault and natural faulted testing with different drive train components. Experience shows that naturally faulted articles add significant value to CBM practices since they are closely related to actual component failures in the field. The use of seeded faults can be informative but experience has shown that it is difficult to choose an appropriate seeded fault to represent the desired failure mode. As such, care needs to be taken to choose seeded faults that have the necessary fidelity to meet test objectives.

INTRODUCTION

Since 2007, the University of South Carolina's (USC) Condition-Based Maintenance (CBM) test facilities have accumulated invaluable testing experience via thousands of hours of component testing. Within the USC test facility is a Tail Rotor Drive Train (TRDT) test stand capable of being modified to test new and existing drive train components of military and civilian aircraft, including the ARH-70, AH-64D, CH-47, and UH-60 drive trains. The test stand was designed to facilitate a scientific understanding of aircraft component conditions as they relate to TAMMS-A inspections, vibration signals, health monitoring systems output, and other data. This scientific knowledge is achieved through component testing of articles.

An important part of CBM is the component testing of faulted articles (components with damage) as it allows verification of existing condition indicators (CIs) with known faults and maintenance actions. It also allows for improving existing CIs by determining optimal thresholds to maximize true positives and minimize false positives for identification of failure modes. Component testing can be pursued in an exploratory manner to establish a new condition indicator. Unfaulted and faulted components are tested to understand the differences in vibration signatures between the two. Faulted components are tested until failure or near failure condition while fault progression is tracked. This allows for more accurate predictions with respect to remaining useful life. Tear Down Analysis (TDA) is used to determine the actual condition of components that have associated CI values. Faulted articles undergo a TDA in order to correlate back to the test stand data. It is impractical to tear down every component, thus the assumption is that the vast majority of components are unfaulted or green. The data from faulted articles along with confirmation evidence from TDA are used to validate newly developed condition indicators (Figure 1).

Faulted articles can fall into two categories: seeded faults and natural faults. Both of these approaches have their advantages and disadvantages with respect to CBM and the development of diagnostic and prognostic algorithms. The paper discusses both of these approaches and presents three

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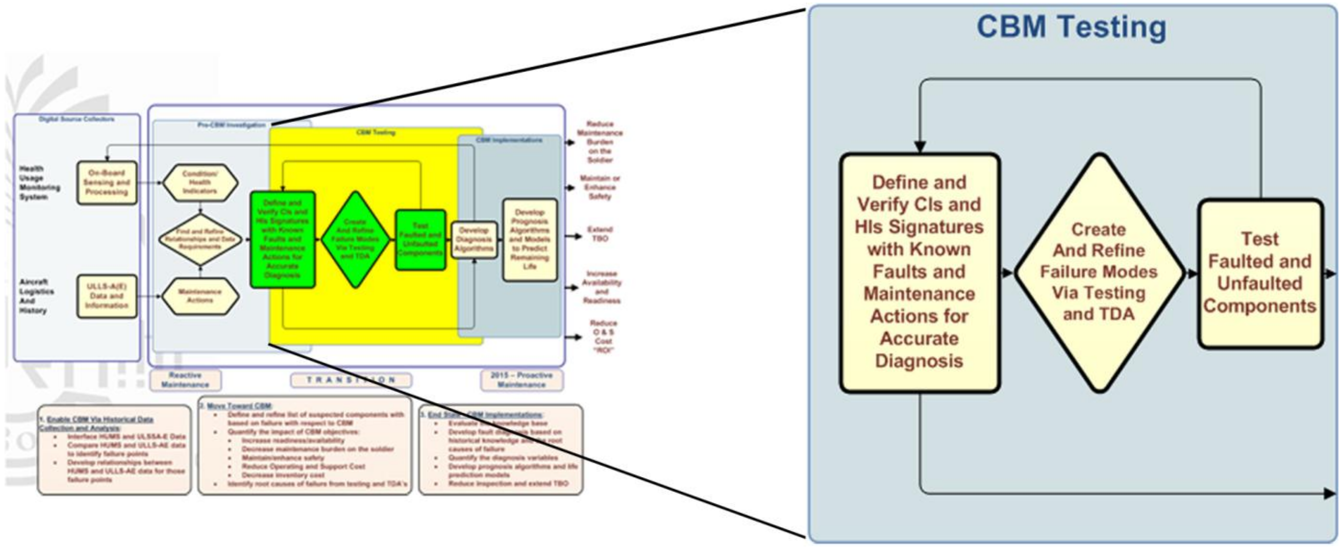


Figure 1. Component Testing Phase of the Roadmap for Condition-Based Maintenance at the University of South Carolina

case studies covering the two methods and the insights gained from the experience.

BACKGROUND AND HISTORY

The CBM program at USC started in 1998. Initially, the program started as a cost-benefit analysis for the Apache and Chinook helicopters of the on-board vibration monitoring system compared to the gold standard, the ULLS-A logistics database. The initial CBM project was a success showing potential cost savings with the on-board vibration monitoring system (Ref. 1-2). The program's next logical step for expansion was to develop as a testing site for the aforementioned sensor monitoring system. Initially, the concept was to develop single component test capabilities. A stand-alone single component test stand would not take into account items such as vibration propagation, system dynamics and to capture system level effects from coupled loading. While failures or system anomalies could be detected on test components, it would be challenging to perform root cause failure diagnosis if the source of failure is located beyond the component. Consequently, the CBM program has continued into what is now an integrated system (multi-component) test stand. As previously mentioned, the CBM test facility now contains an entire tail rotor drive train system because the drive train system is a significant source of vibration for other parts of the aircraft not directly associated with the tail rotor drive train. Currently, faulted articles are routinely tested on the test stand. Component testing on the test stand can involve a single faulted component (with multiple seeded faults) or multiple faulted components (with different faults) at a time.

The selection of a component is based on an initial investigation stage. This stage is driven by historical data sources (i.e. HUMS and ULLS-A data). By integrating and defining relationships between the two sources, the failure points which would potentially provide the most value added through CBM testing can be identified. This in turn would determine the components to be selected to determine the direction for experimental fault testing. Test stand data from fault testing provides the basis for the development of condition/health indicators and eventually predictive tools as part of a smart predictive system. An example of component selection is provided in the second case study.

SEEDED FAULTS

A seeded fault is a fault deliberately produced on a component for testing purposes. Some examples of seeded faults are i) adding sand (to simulate a desert environment), ii) adding saltwater (to simulate a sea environment) and iii) low grease (to simulate a loss of grease). One advantage of introducing seeded faults is that there would be a one-to-one correlation of the fault with the measured vibration frequency spectrum of the component. By having direct control over the component being tested, the approach turns into a controlled reproducible experiment. Seeded faults can expedite the testing process since it requires less time to seed a faulted component than to wait for a naturally occurring fault in the field. Another benefit of seeded faults is the ability to measure the rate of failure progression and the corresponding changes in CI values. Test data that can correlate CI values with fault severity on an article is invaluable in the development of a smart predictive system.

Furthermore, seeded fault testing can be used to demonstrate that fault signatures are suitably insensitive to variations in test specimen and operating environments. CIs should deliver consistent results across all available test specimens over the full range of expected aircraft operating conditions. With this in mind, seeded fault can also be used for sensor selection, development and placement. Seeded fault testing can confirm that some failure modes and fault conditions are not reliably detectable by CIs and should not be transitioned to a CBM system. Seeded fault testing may reveal that an impending fault may not exhibit any measurable indication prior to failure, and therefore may not be a good CBM candidate.

One potential drawback is that the seeded faults could have low fidelity with the actual field condition of the component. Fidelity is defined as the degree to which the faulted article replicates its counterpart's behavior in the field. The determination of a seeded fault's level of fidelity is a non-trivial matter. Consequently, experimental results from a low fidelity seeded fault are not transferable to a naturally faulted component in the field. The same CIs and/or thresholds for the seeded fault would not be applicable to identifying a similar fault in the same component from the field. The seeded fault should ensure that it is representative of the component on the aircraft.

NATURAL FAULTS

A naturally faulted article (also commonly referred to as field faulted) is one in which the article has become damaged from actual usage in the field. Articles can be removed from the field for testing with known faults. Sometimes the exact source of the problem is unknown and articles are chosen based on maintenance records and the on-board vibration monitoring system. This requires examining records from multiple aircraft to discern a common problem among them and then extracting the suspected articles from the field for further testing.

The advantage of this approach is that the tested article has a high fidelity with the condition in the field because it was taken directly out of field service. Thus the test results are directly applicable or transferable to future field fault analysis.

A possible disadvantage with this approach is that there might be increased difficulty to correlate failure with root cause. Also, the field articles are not reproducible for testing since no two field articles experience the exact same usage. Also, this mode of testing can be time-intensive since the testing process is dependent on waiting for a naturally occurring fault in the field. This also decreases feasibility of validation and causes potential delay of implementation. Tracking fault progression with natural faults is also limited since it is unlikely that the field article will be removed at the incipient stages of failure for testing. Fault progression tracking would likely be limited to the latter stages of failure modes.

CASE STUDIES

In this section, three case studies are presented with a discussion of the research and testing results. The case studies are as follows:

1. Seeded fault testing of hanger bearings
2. Seeded fault testing of a tail rotor gearbox with a discovery of a natural fault
3. Natural fault testing of an intermediate gearbox

Seeded Fault Hanger Bearings Study

The objective of the hanger bearing seeded fault test was to examine whether existing CIs would respond to failure modes simulated by seeded faults (Ref. 3). A Functional Hazard Assessment (FHA) on the hanger bearings identified and classified possible failure conditions such as spalling and thermal runaway induced by loss of lubrication, corrosion, temperature degraded grease, sand/dust contamination, or saltwater contamination. A sheared or seized tail rotor shaft would result in loss of aircraft anti-torque. Consequently, this could result in the crew being unable to control the aircraft and continue safe flight possibly leading to loss of crew and aircraft. As a result of the FHA, the following seeded faults for the test were chosen as follows:

i. cut grease seal
ii. reduced grease
iii. heat degraded grease
iv. fine sand contamination
v. machined spall
vi. coarse sand contamination
vii. saltwater corrosion

Seeded fault tests were performed on helicopter hanger bearings on USC's TRDT test stand. Some test articles had more than one seeded fault and some runs tested more than one faulted article at a time. For the seeded faults 1-5 listed above, over 8000 hours of testing were done on these seeded fault articles with no substantial evidence that the CI values were responding (i.e. increasing) as expected. Specifically, the CI values never exceeded the red (lack of functionality) or yellow (component's functionality is reduced) threshold setting.

Thermal runaway was also not detected as thermocouple readings for the hanger bearings tended to stay level over the course of the test. Moreover, TDA was performed on each article after hundreds of hours on the TRDT test stand. Each hanger bearing article was given a color code rating of green. According to the TDA color code scorecard, green represents either a fully functional operational component and no maintenance is required or a component that is functional with degraded performance (as with the faulted hanger bearing articles) and needs to be monitored frequently (Ref. 4). This indicates that the seeded faults chosen did not have a high fidelity in representing the failure modes and as a result, the seeded faults were not detectable by existing CIs.

In these cases, the evidence showed that the articles were unfaulted (i.e. functional components with degraded performance). However, not all the testing was wasted effort. Since the hanger bearing articles were not indicating failure, the tests were now viewed in another light; as endurance tests to achieve CBM credit. CBM credit is defined as the approval of any change to the maintenance schedule of a component such as an extending operating time between maintenance, overhaul or inspection. In particular, CBM credit was sought for extending the time between overhaul (TBO) for the hanger bearing from 2750 to 3250 hours. The L10 operational life of the grease in the hanger bearings, with temperature as the primary concern, is estimated to be a minimum of 6000-6500 hours. The accelerated grease life testing demonstrated that a hanger bearing with degraded/contaminated grease was capable of operating satisfactorily for a minimum of 3250 hours beyond the point of grease degradation that would be expected after 6000-6500 operational hours. These two pieces of information helped support the technical basis for a hanger bearing TBO extension. What initially started as a seeded fault test transformed into a component endurance test for CBM credit for extending TBO.

Among the successful seeded faults were the saltwater-corroded hanger bearings. These articles showed elevated CI readings in the yellow and red regions. The TDA color code for these articles was red. The results suggested that the threshold for the amplitude demodulated bearing CIs could be lower for the field. The CI data along with evidence from the TDA provided the confirmation for the fault.

In another analysis, the seeded fault data was used to verify the aft hanger bearing energy CI threshold limit (Ref. 4). For the saltwater-corroded bearings, the current yellow threshold limit, 7g, effectively separated the faulted bearing from baseline values (Figure 2).

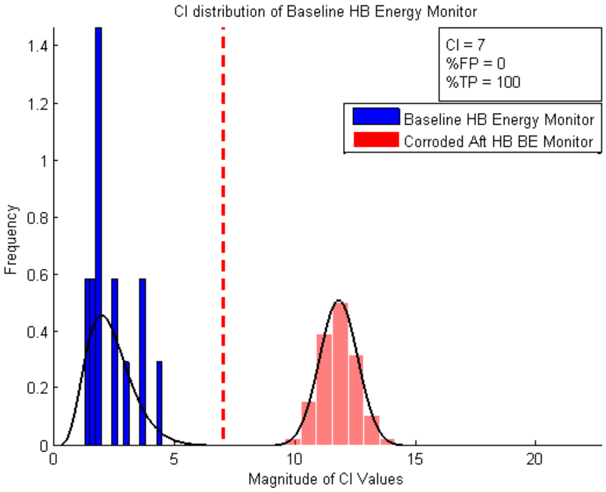


Figure 2. Distribution of Aft Hanger Bearing Energy CI values for saltwater corrosion (Source: ADS-79C HDBK)

Similar finding were found for coarse sand contamination in that the same CI was able to distinguish between coarse sand contaminated bearings from baseline values. However, for fine sand grease contamination this was not the case as the yellow threshold was set too high to detect the vast majority of readings (Figure 3).

The analysis showed that one CI could be used to detect multiple root causes (saltwater-corroded and coarse sand grease contamination). The analysis also showed that the same CI could be virtually ineffective in testing similar seeded faults (fine sand grease contamination). Figure 3 shows that a lower yellow threshold (CI = 3.78) would have been able to distinguish between the two groups with a high true positive rate (99.7%) and high true negative rate (93.3%). However, this would not have been supported by the TDA and the resulting color code rating of green given to the fine sand contaminated article. Thus, verification of CIs and seeded faults by tear down analysis is necessary to confirm the condition of the article.

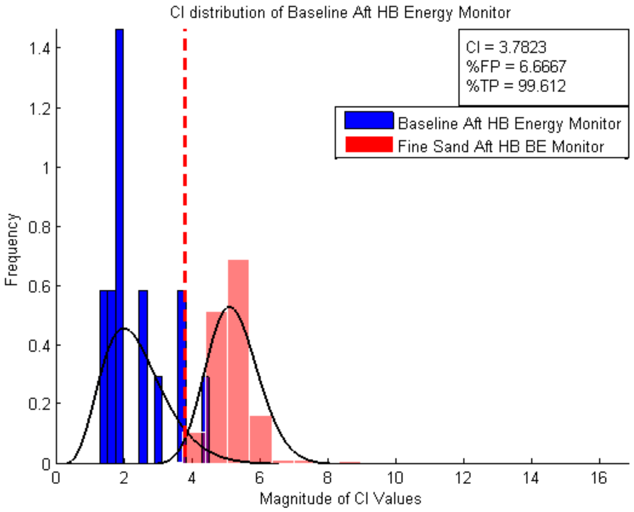
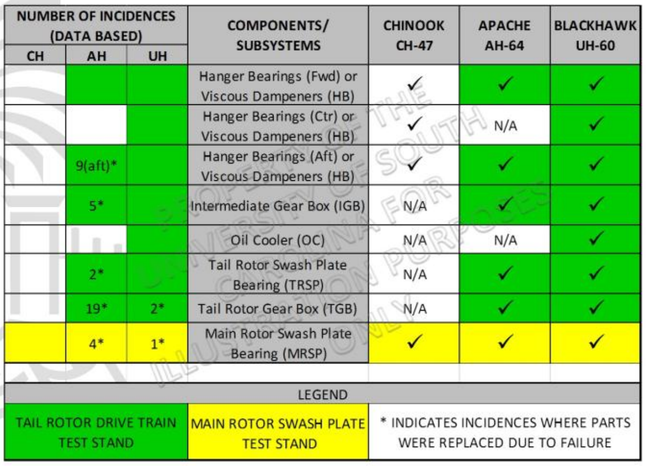


Figure 3. Distribution of Aft Hanger Bearing Energy CI values for fine sand contamination (Source: ADS-79C HDBK)

Tail Rotor Gearbox Output Seal Study

The AH-64D tail rotor gearbox (TGB) assembly is the subject of our second case study. This aircraft model and component were chosen based on a systematic initial investigative stage. As part of its initial CBM effort, USC and the Army identified the type of components to be tested based on Unit Level Logistics Support – Aviation (ULLS-A) data and mission databases over a period of several years (Ref. 5). The ULLS-A system was used to track fields such as: part serial number, cost, man hours for installation and troubleshooting, test flight hours for confirmation or operational crew hours, whether part is related or not to vibration, and results from tear down analysis (if available). Data from multiple aircraft models at different establishments and environments were obtained accounting for over 35,000 flight hours and millions of data records. Parts that were replaced due to failure were tabulated. The data showed that a high number of incidences (n=19) occurred for the AH-64 tail rotor gearbox (Figure 4). Upon further investigation of the data, it was determined that the leading cause (in 39% of the cases) of TGB removal was leaking liquid (i.e. grease) (Table 1). Thus, the case of the AH-64 tail rotor gearbox leaking grease through its output seal was determined to be a prime candidate for component testing (Ref. 6). The associated grease loss, in the field, was sufficient grounds for immediate grounding of the aircraft (for fear of failure of the static mast ball bearings) and an unscheduled maintenance action for the complete replacement of the tail rotor gearbox.



NUMBER OF INCIDENCES (DATA BASED)			COMPONENTS/ SUBSYSTEMS	CHINOOK CH-47	APACHE AH-64	BLACKHAWK UH-60
CH	AH	UH				
	🟩	🟩	Hanger Bearings (Fwd) or Viscous Dampeners (HB)	✓	✓	✓
		🟩	Hanger Bearings (Ctr) or Viscous Dampeners (HB)	✓	N/A	✓
	9(aft)*	🟩	Hanger Bearings (Aft) or Viscous Dampeners (HB)	✓	✓	✓
	5*	🟩	Intermediate Gear Box (IGB)	N/A	✓	✓
		🟩	Oil Cooler (OC)	N/A	N/A	✓
	2*	🟩	Tail Rotor Swash Plate Bearing (TRSP)	N/A	✓	✓
	19*	2*	Tail Rotor Gear Box (TGB)	N/A	✓	✓
🟨	4*	1*	Main Rotor Swash Plate Bearing (MRSP)	✓	✓	✓

LEGEND		
🟩 TAIL ROTOR DRIVE TRAIN TEST STAND	🟨 MAIN ROTOR SWASH PLATE TEST STAND	* INDICATES INCIDENCES WHERE PARTS WERE REPLACED DUE TO FAILURE

Figure 4. Part Failure Incidences via ULLS-A Data for three different aircraft models and eight components / subsystems

Table 1. Causes of Tail Rotor Gearbox Removal

Reason	Pct.
Leaking (liquid)	39%
Seal/Gasket Blown	10%
Worn Excessively	10%
Scored	9%
Grooved	7%
Beyond Specified Tolerance	6%
Pitted	4%

The objective of the study was to demonstrate that the aircraft could continue to operate with a leaking output seal until the aircraft reached a major maintenance event (250 hours interval). A secondary objective was to characterize the failure of the static mast ball bearings. A seeded fault was introduced with the removal of some of the seal material and a hoop spring to induce a leak in the output seal. The static mast ball bearing was anticipated to fail because of this seeded fault.

During the test, it was discovered that the grease was moving from the main gear compartment to the static mast. This caused the gear mesh surface to be starved of grease eventually leading to catastrophic failure of the input gear teeth. Figure 5 shows images of the fault progression for the gear mesh tooth at seven time intervals for one of the test articles. It also shows how the tooth wear could be related to temperature, vibration and grease in a hypothetical model for data fusion for diagnostic algorithm development. This data fusion of different condition indicators is part of the CBM analysis envisioned as part of a smart predictive system (Figure 6).

While the seeded fault test did not characterize a failure of the static mast ball bearings, it discovered a previously unknown natural fault (grease movement between two compartments of the tail rotor gearbox). The conclusion was that a leaking output seal can cause gearbox failure only if the main compartment grease levels are not properly maintained. Thus by adding more grease to the gearbox, the gearbox can continue to operate nominally without a need for an unscheduled maintenance action.

Unbeknownst at the time, the seeded fault test was also testing a naturally faulted component. While the seeded fault testing did not produce the anticipated failure mode, the testing and subsequent discovery of the natural fault allowed the test to meet its main objective of demonstrating that the aircraft could continue to operate with a grease leak until its next major maintenance event. Not only that, but it resulted in the publication of several Airworthiness Releases changing maintenance practices in the field. In this case, the natural faulted article provided more value added than the planned seeded fault test.

Intermediate Gearbox Oil-Grease Study

The AH-64 intermediate gearbox (IGB) was found to eject large volumes of grease through its breather port (Ref. 7). This required the aircraft to land for immediate maintenance. This natural fault occurred even after the IGB was recently serviced. The study sought to compare the effects of using oil vs. grease in the IGB with respect to the ejection of lubricant, temperature and vibration. In this case, seeded fault testing would have been challenging since it would be difficult to create a fault that would emulate the burping of lubricant.

The first test had the gearbox burping foamy oil for the first hour of testing before subsiding. The volume of oil lost through burping was about half of the initial amount. The oil level was refilled to its original amount and no more oil burping took place for the rest of the tests (about 200 hours). The use of oil also lowered the IGB operational temperature from 225°F to 175°F after a week of operation. With regards to the IGB CIs, few major differences were observed, though several CIs did change when oil was used in the article. Though these vibration variations were slight and did not affect the performance of the IGB, they do serve to highlight

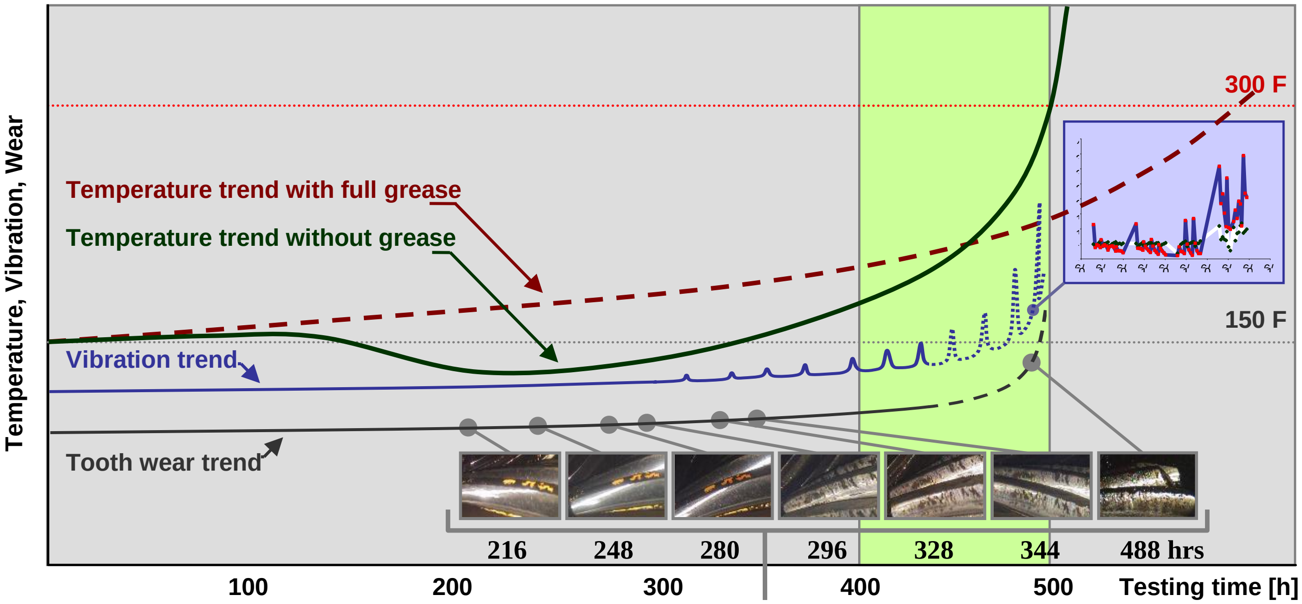


Figure 5. Diagnostics modeling: hypothetical data fusion of temperature, grease, vibration and tooth wear for the tail rotor gearbox

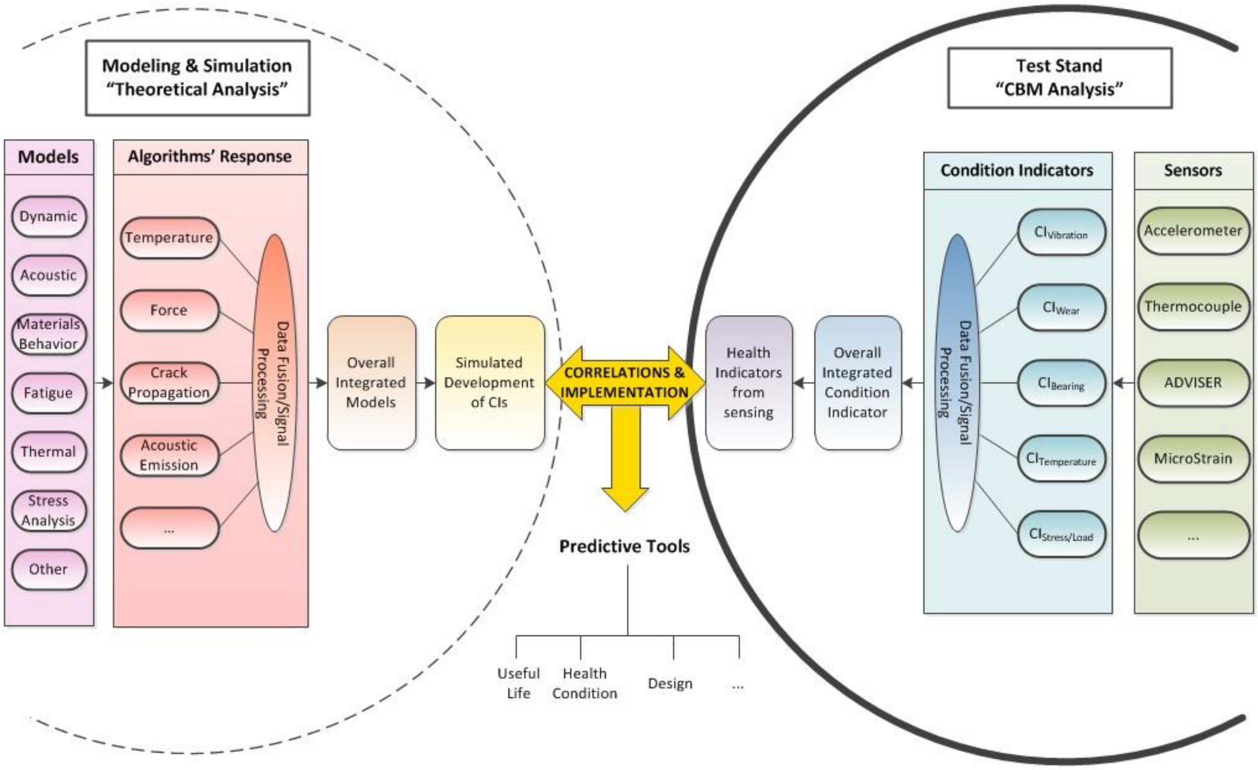


Figure 6. Data fusion of different CIs from figure 5 is part of the CBM analysis envisioned as part of a smart predictive system.

the fact that lubricant does have some measureable impact on the vibration levels of the component. There were no indications of oil outperforming grease with respect to the CIs. Overall, the results showed that the oil did not have any negative effects on the IGB and that the component was healthy throughout the testing.

The testing of the natural faulted article was conducted to address the concern about grease being ejected from the breather port on the IGB. The use of oil instead of grease caused the natural fault to subside. This study also served to examine the discernible differences between the two lubricants. Because the use of oil did not bring on any adverse effects, the results warrant further study of oil as an IGB lubricant and can assist in the design of future gearboxes.

CONCLUDING REMARKS

Experience shows that naturally faulted articles add significant value to CBM practices since they are closely related to actual component failures in the field. The use of seeded faults can be informative but experience has shown that it is difficult to choose an appropriate seeded fault to represent the desired failure mode. As such, care needs to be taken to choose seeded faults that have the necessary fidelity to meet test objectives.

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