Application of Aeronautical Design Specification 79 to the UH-60L Accessory Gearbox Generator Drive Bearings

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Abstract

The US Army has been installing the Goodrich Integrated Vehicle Health Monitoring System (IVHMS) on its fleet of Blackhawks for nearly a decade. More than one thousand UH-60 aircraft are now equipped, including the entire UH-60M fleet. IVHMS health predictions have been correlated with component physical condition through 33 tear down analyses (TDAs), resulting in an overall system performance rating, or *batting average*, of 50%. The batting average is a rating that shows the system's overall capability, which takes into account the four fundamental aspects of a HUMS system according to Aeronautical Design Specification (ADS) 79: *Detectability*, *Identifiability, Separability*, and *Accuracy*.

The ADS lays the groundwork for certifying the HUMS such that maintenance intervals can be removed or extended and component life may be correctly quantified. This paper will explore the ability of the IVHMS to predict the Remaining Useful Life (RUL) of the UH-60 Accessory Module Generator Bearings and is based on three completed TDAs with associated HUMS mechanical diagnostics data, in accordance with the ADS. The usefulness of such a diagnostic will result in increased aircraft readiness, improved mission planning, and a reduction in mission abort rates.

Four UH-60 Accessory Modules have been removed for bearing exceedances and three have undergone TDA. These TDA reports and their associated vibration data will be presented. Demodulated frequency domain data for bearing monitoring will be presented and compared with alternate methods for fault detection on the same dataset. ADS-79 requirements for certification will be shown and meaningful vibration diagnostic thresholds will be presented. RUL of the component will be based on the presumption that a built-in chip indication in the oil system marks the end of the bearing's RUL. Results of this study will show the four fundamental aspects of the HUMS and the process for acquiring certification will be completed. This certification demonstration will serve as a guide for successful application of ADS-79 on other components and for non-US Army entities.

Introduction

To date, the US Army Condition Based Maintenance (CBM) program has equipped more than 1,000 UH-60 series aircraft with Health and Usage Monitoring Systems (HUMS). HUMS are comprised of digital source collectors (DSCs), suites of accelerometers and other sensors. All drive train gears, shafts, and bearings are monitored by these systems. A variety of signal processing algorithms known as Condition Indicators (CIs) have been developed to detect incipient faults in gearbox bearings using accelerometer data. These CIs have been developed and refined by academia, government agencies, and HUMS vendors.

The traditional methods of calculating bearing vibration-based condition indictors use vibration energy found near gearbox and bearing natural frequencies as well as individual frequencies known as *fundamental bearing fault frequencies*. These fundamental frequencies are determined by the rotational speed of the supported shaft and the geometries of the bearing elements. They are fixed during nominal aircraft operation.

The Army has amassed nearly a decade of DSC CI data that includes thousands of hours of healthy and faulted bearing vibration signatures. The vibration data and CI trends have been cross-referenced with historical information about the removal of gearboxes and their associated tear down analyses. As part of the CBM program, it is desired to continuously improve the functionality of the bearing monitoring functions in the DSCs. CI effectiveness is graded according to Aeronautical Design Standard Handbook (ADS-79-HDBK) [1] for Condition Based Maintenance Systems for US Army Aircraft Systems. The ADS-79 prescribes required detection rates for CIs and other vibration health measurements in order to extend bearing life and meet CBM objectives. As in the medical field, ADS-79 uses the terms true/false and positive/negative in categorizing the presence of, and successful detection of a faulted state. Further explanation of these terms can be found in Table 1.

	Faulted State Present?	State Correctly Identified?
True Positive (TP)	**Yes**	**Yes**
True Negative (TN)	**No**	**Yes**
False Positive (FP)	**No**	**No**
False Negative (FN)	**Yes**	**No**

Table 1 ADS-79 Fault Detection Success Terms

FPs and FNs impact the airworthiness of the CBM system and therefore must be minimized.

This paper is a compilation of accessory gearbox bearing (AGB) failures that have been recorded by the Integrated Vehicle Health Monitoring System (IVHMS). Algorithms that are automatically calculated by the on-board systems are presented, as are algorithms that have been developed more recently. These additional algorithms have been *post processed* using the recorded data.

The AGB transmits power from the engine input gearbox to the electrical generator and hydraulic pump of the UH-60 aircraft. It is a redundant gearbox with two identical gearboxes, on the left and right sides. The gearbox contains two ball bearings for the generator and two roller bearings for the hydraulic pump. A diagram of the AGB is given in Figure 1. The cases presented in this paper will focus on chip events caused by the generator drive ball bearing set, a duplex roller bearing separated by a spacer ring, items 20 and 21 respectively in Figure 1.

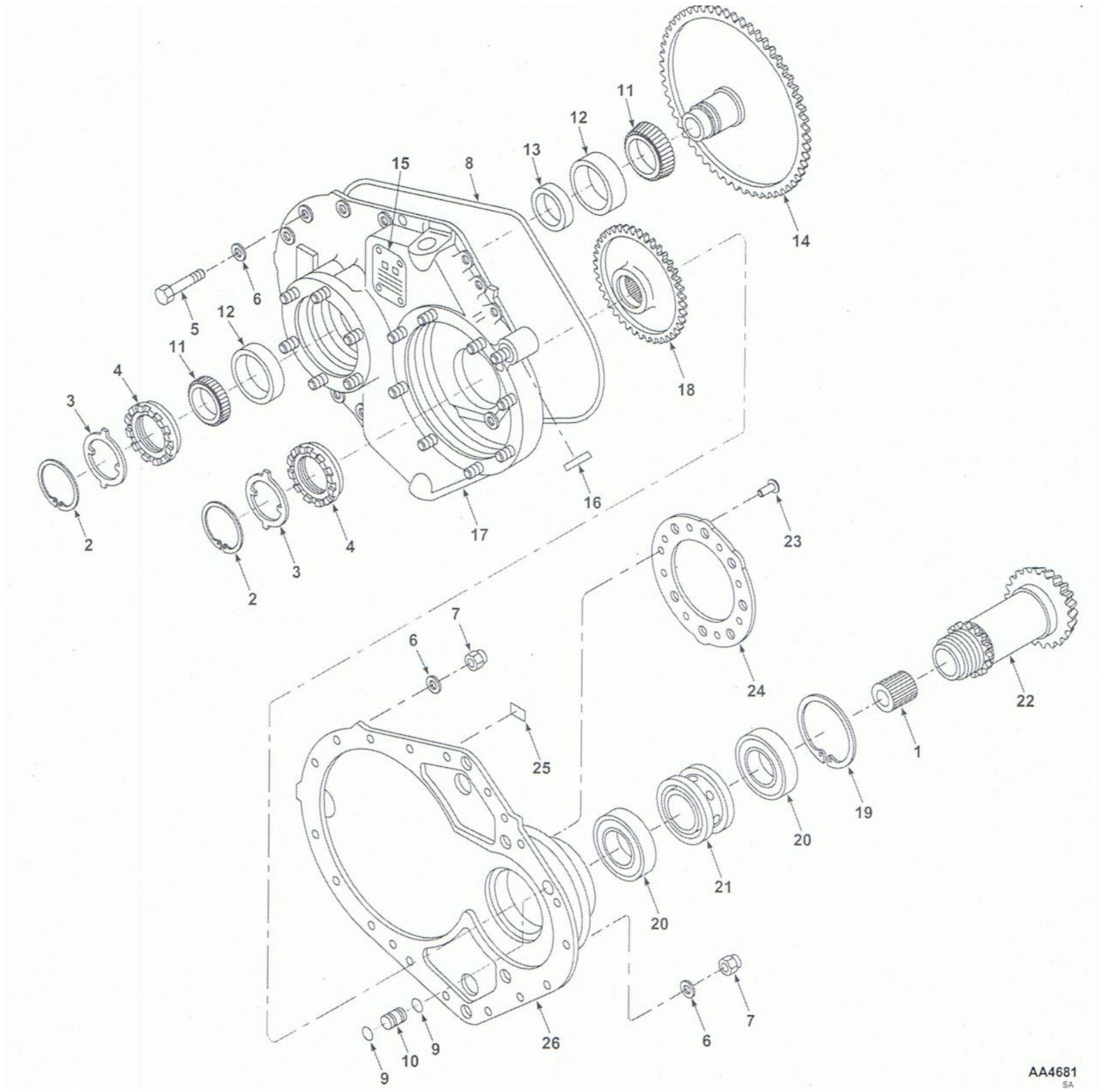

Figure 1 H-60 Accessory Gearbox Diagram

As part of the Army CBM project, tear down analysis (TDA) is completed on gearboxes that have known failures and associated CI and raw data records, like time and frequency domain information, for comparison. The TDA is a detailed post-mortem physical inspection of the gearbox. Fault dimensions and severity are noted so that condition status may be assigned to the gearbox. This condition status presumes knowledge of remaining useful life (RUL) given the physical condition of the gearbox components. AGB generator bearings present a special circumstance for RUL estimates: Although the bearings could continue to operate for some time, ferrous debris causes an illumination of the gearbox chip light. Excessive chip events require the replacement of the gearbox, meaning the RUL of a bearing that "makes metal" is effectively zero hours.

The IVHMS records a portion of the time sample associated with a bearing CI calculation when the system detects an unhealthy condition (Health Indicator in yellow or red status), or if the IVHMS has been commanded to do so administratively by the user. Furthermore, the IVHMS records two transforms of the time domain data, the magnitude of the frequency domain, 8193 spectral lines up to 52.0835 kHz, and the envelope spectrum, 2049 lines up to 5.208 kHz. Each of these three raw data streams is used to calculate the unique CIs associated with each of the bearings inside the AGB.

Discussion

High confidence in the diagnostic system is a major goal of any CBM initiative because high confidence increases maintainer and pilot confidence in the diagnostic outputs and justifies the cost of installing the DSC. The DSC systems installed by the Army therefore must subscribe to the tenets of ADS-79. The following characteristics of system confidence are defined by the ADS:

- Accuracy; The extent to which a diagnostic measure correlates to the severity of the fault.
- Detectability; The extent to which a diagnostic measure identifies the presence of a particular fault. Detectability should relate the smallest fault signature that can be identified at the prescribed false alarm rate.
- Identifiability**;** The extent to which a diagnostic measure distinguishes one fault from another that may have similar properties.
- Separability; The extent to which a diagnostic measure differs between a faulted condition and healthy condition.

These four characteristics are absolutely critical to the development of a DSC and for any indications on board the aircraft; each can be objectively quantified and compared between cases. The tear down analysis (TDA) shows the level of damage and which components were damaged. Without TDA, the process of improving the DSC is not possible.

The CBM program is focused on two avenues for improving DSC function and attaining *on condition* status. The first focus is on components with a retirement life or maintenance intensive inspections. There is an obvious goal, a CBM Credit, to be attained through monitoring these items. These components require the largest investment of engineering dollars to develop and have stringent requirements which are necessary to ensure airworthiness. Thus removing a retirement life or inspection can be very difficult through CBM, and always expensive.

In contrast, components without a retirement life or inspection requirement can benefit from CBM relatively quickly and inexpensively. The maintainer therefore benefits from the increased readiness and knowledge of potential future unplanned maintenance. Since the baseline risk of operating the aircraft is not increased, even experimental and developmental condition indicators can be used for diagnostics. Especially important is the use of thresholds that are not going to produce false alarms until the diagnostic has properly matured.

It can be seen therefore that there are both pros and cons to monitoring components with no retirement lives. The diagnostics can be focused on failure modes that occur most frequently for the component rather than all possible failure modes which are often required regardless of frequency of occurrence. Furthermore, components that are to *go on condition* via CBM credits require more justification of types of failure modes to monitor; it is often difficult to justify which failure modes are possible to ignore and continue to maintain the airworthiness of the aircraft. Unfortunately it is often not possible to discover the reasons for currently implemented maintenance actions and therefore impossible to justify the amount of data required for *on condition* status.

When increasing the capability of the DSC but not going *on condition*, the number of tear down analysis samples is not required to be large because high confidence is not required. The project manager is only required to show that there is a benefit to setting thresholds to increase readiness and facilitate enhanced maintenance. This results in a CBM process that is fast and cheap to employ as well as being effective for the maintainer.

It is important to note that setting these thresholds based on a small dataset of teardown information can result in consequences for the CBM program. It is possible that the thresholds could be set incorrectly and could require several software changes as more information about the recommended maintenance is learned in the field. Furthermore, as has been seen by the Army [2], it can be difficult to measure return on investment for these types of monitored components. For example, increased readiness of available aircraft is not easy to measure in dollars.

ADS-79, paragraph 5.9.1 specifically states that:

> Advantages to this approach are: relatively low initial cost approach that does not require a large number of sample specimens to demonstrate algorithm reliability for each failure mode; ability to enhance maintenance by focusing on specific failure modes versus all failure modes of complex components; relatively short timeframe involved prior to field implementation due to the reduction in test requirements; and the ability to gather data during normal aircraft operation to facilitate verification/validation efforts.

Regardless of the potential problems that may be caused by setting diagnostics thresholds for components without retirement lives, in the long term CBM project, the improved diagnostics will result in reduced mission aborts, increased readiness, improved mission planning and a reduction in the potential for collateral damage caused by failure of the module/gear/bearing that actually has a fault. The diagnostics will also impact the logistics/supply chain management as well.

Methodology

The ADS-79 documentation (Paragraph C.2.4) gives specific guidance for development of mechanical diagnostics. The authors have applied this guidance to the AGB and refined the thresholds based on the outcomes of the entire process, which is outlined in paragraph C.2.4. The authors have tailored this application and followed the following steps:

1. Physics of Failure Analysis
2. Detection Algorithm Development
3. Fault Correlation Data Mining
4. Fault Validation/Seeded Fault Analysis
5. Inspection/Tear Down Analysis
6. Electronic and Embedded Diagnostics (BIT)/(BITE)

Physics of Failure Analysis

The physics of failure regarding the current DSC capabilities, namely vibration monitoring, are well understood for the AGB. The AGB failure modes all project from bearing, gear, and shaft failure. For the bearings, the loss of material from bearings and bearing race surfaces leads to the formation of hard particles in the oil and can result in the seizure or disintegration of the bearing. Failure of the bearings therefore results in a chip indication at the chip detector, which further causes a precautionary landing. The oil system for the UH-60 AGB is connected to the Main Module which in fact is connected to the other gearboxes and thus it is possible for chips in the AGB to cause collateral damage. Thus, early detection of chips produced by the bearings is important to the health of the entire aircraft.

Detection Algorithm Development

The CIs utilized in the IVHMS are intended to monitor all potential gear and bearing failure modes caused by spalling, galling, pitting, and other severe wear that would result in the machining of the metal surfaces. The bearing diagnostic CI suite primarily utilizes an amplitude demodulation algorithm which envelopes (filters) around the assumed bearing and gearbox natural frequencies between 13 and 18 kHz. This envelope is based on the previous experience of Goodrich engineers [3]. In the implementation of the IVHMS on the UH-60 aircraft, there was no testing to determine the individually desired envelopes for each bearing.

As part of the CBM program, the Army has been improving the performance of the window by making recommendations to measure the best enveloping settings. As has been demonstrated by the on-board system, from the beginning of the project, the AGB bearing demodulation window appears to be set correctly. Four total cases of failures, of which three are documented, have resulted in successful detections of faults.

For most other cases, the Army recommends a comprehensive understanding of the modal characteristics of the gearboxes and their mount structures to correctly define the demodulation windows of all the bearings. Techniques such as seeded fault analysis and frequency response function estimation can be used to identify the appropriate bearing windows.

Fault Correlation Data Mining

The data collected on the IVHMS has been scrutinized by the Army using several methods. As demonstrated by Dempsey [4], Receiver Operating Characteristic (ROC) curves can be used to determine thresholds based on two different populations of data. For example, the data from a faulted gearbox can be realized as a histogram versus the remaining fleet. With the ROC analysis, a threshold is set such that FPs and FNs are less than the acceptable levels. ADS-79 gives acceptable levels based on the criticality of the component under question. For the case of the AGB, being that it is redundant and already on condition via the chip detector, the bar is set low and an allowable FP or FN rate could be 10% or more if the project manager so approves.

The Army also utilizes automated fault detection software to screen the data as it is sent in from the field. The engineers and relevant analysts are alerted when CIs exceed thresholds set based on statistical methods or known physical phenomena. Once identified, outliers can be investigated thoroughly and additional data from the field can be requested. The data that is sent to the engineers contains raw data whenever the built-in thresholds are exceeded. Raw data can include limited time domain data directly from the sensor as well as intermediate data, such as the Fourier Transform used by the system for on-board calculations.

Figure 2 shows an example of a histogram used to determine the appropriate threshold for an AGB fault. In the example given in Figure 2, for ball energy the data is well separated with 88% of the faulted data above and a less than 1% of the healthy data above the indicated threshold value. With this information all of the principle areas of CI performance can be demonstrated. The fault is detectable and the CI is accurate and separable. The identifiability of the fault can only be tested when and if a nearby gear or shaft fails. To date, all nearby faults have been correctly isolated by the appropriate CIs. This includes gear and generator drive shaft faults. Figures 2-7 give histograms for each of the five primary IVHMS CIs for the generator bearings. The UH-60L fleet distribution is in blue, comprised of approximately 285 unique aircraft. The red distributions are the combined faulted datasets from 90-26272 and 92-26454 for one week prior to replacement.

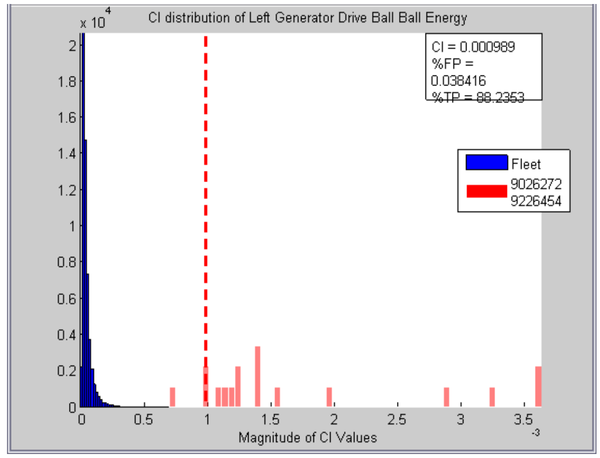

Figure 2 Faulted aircraft distributions compared to the assumed healthy fleet.

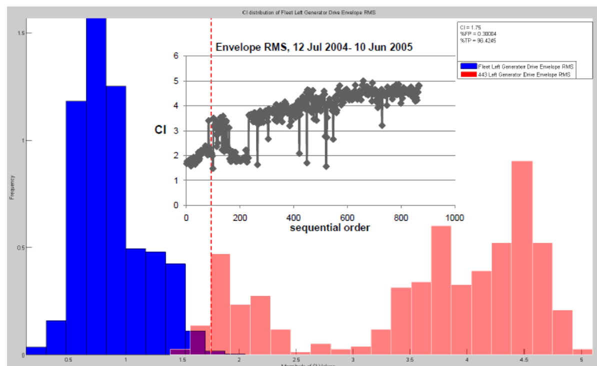

Figure 3 Ball Energy Histograms

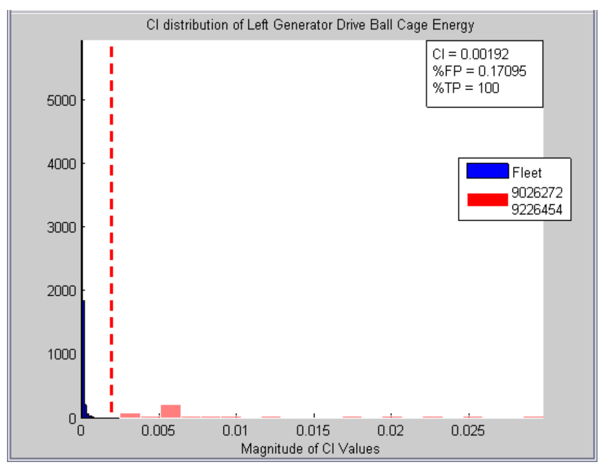

Figure 4 Cage Energy Histograms

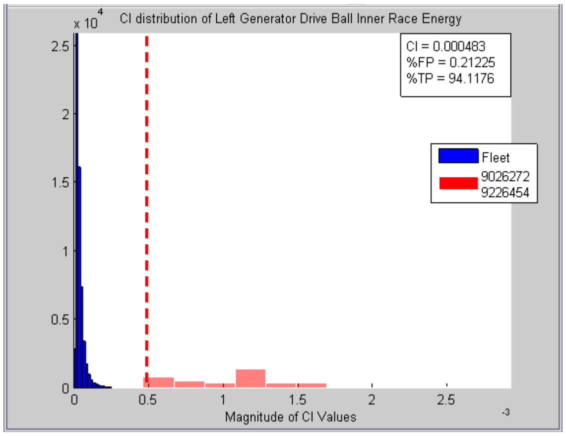

Figure 5 Inner Race Distribution

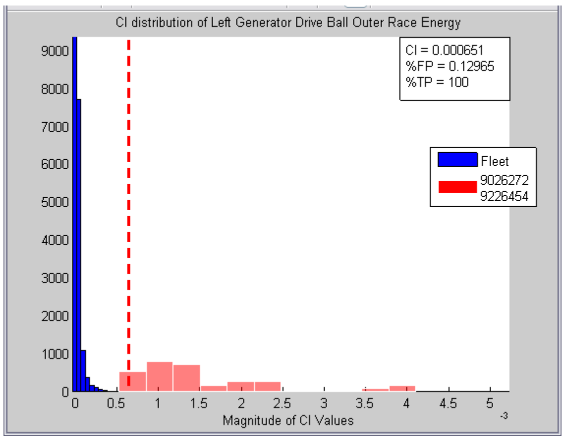

Figure 6 Outer Race Histograms

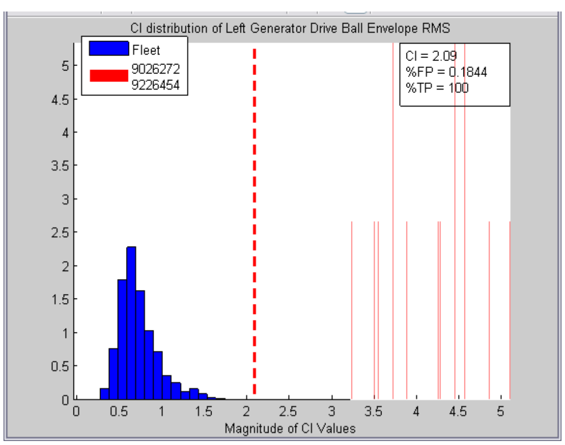

Figure 7 Envelope RMS Histograms

An example ROC curve for these histograms is given in Figure 8. Thresholds developed from these ROC curves are given in Table 2.

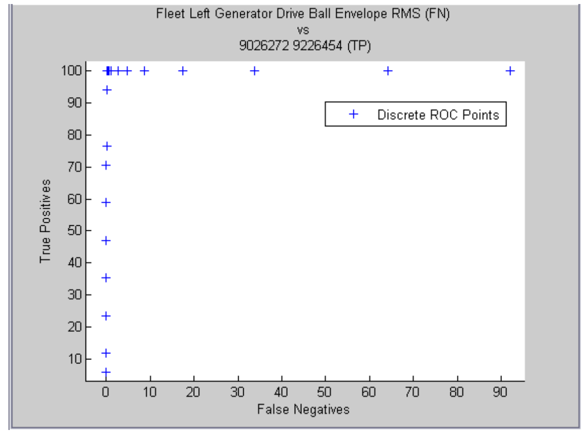

Figure 8 Example ROC curve for threshold setting showing known faulted aircraft.

Left Generator Drive Ball, Accessory Output Sensor		
CI Name	**Red Threshold**	**Separation (%)**
Ball Energy	0.000989	85.5/0.07
Cage Energy	0.00192	85.5/0.2
Inner Race Energy	0.000483	87.1/0.04
Outer Race Energy	0.000651	85.5/0.07
Envelope RMS	2.09	91.9/0.03

Table 2 Thresholds

Fault Validation/Seeded Fault Analysis

The redundant nature of the AGB means even a complete gearbox failure does not result in the loss of the aircraft. For this reason, and because an ample number of naturally occurring faults have already been observed, seeded fault analysis of the AGB is not necessary.

Inspection/Tear Down Analysis

Fault inspection is done through tear down analysis (TDA). TDAs are accomplished by following the acceptable depot maintenance repair practices for the gearbox or bearing which describe in detail how a component or assembly is to be deconstructed. Proper deconstruction of the gearbox is absolutely necessary, as the process cannot interfere with the actual condition of the target components. It is vital to perform a comprehensive inspection of the gearbox, rather than focusing on the suspected problem area. Targeted inspections, although faster and cheaper, do not provide the *whole picture* of fault progression, collateral damage, or other factors that may have obscured a proper detection.

After the components are freed from the gearbox structure, expert knowledge of the acceptable wear for the component is required to *grade* the bearing and estimate the remaining useful life (RUL). ADS-79 gives a guideline for estimating condition and RUL at the end of Appendix C in Figure C.16. It is reprinted here in Figure 9. The AGBs that have undergone TDA have all been called color condition *RED* which indicates that the component should be removed as soon as possible.

Examples from each of the AGBs that have undergone TDA are shown in Figures 10 through 12. The first AGB failure monitored by the IVHMS is documented by Suggs [5]. Since the completion of that study a new normalization procedure was introduced into the enveloping algorithm and thus the thresholds developed based on that case are no longer applicable.

Platform: ______________ Name: ______________
Component: ______________ Date: ______________

Score Card

Color Code	Operational Capability	Maintenance Action Required	Time Horizon for Maintenance	Impact to Components	Color Determination
	Fully Functional	No Maintenance Required	Form 2410 Remaining Life	No Perceptible Impact to Components/Mating Parts	Green
	Functional with Degraded Performance	Monitor Frequently	> 100 Hrs	Eventual Component/Mating Part Degradation from Light Metal Contamination/Wear/Vibration Translation	Green
	Reduced Functionality	Maintain as soon as Practical	10 Hrs < X < 100 Hrs	Moderate Metal Contamination resulting in accelerated component/mating part degradation	Yellow
	Non Critical <u>and</u> Non-Mission Aborting Failure Mode: Lack of Functionality Results in Red Diagonal*	Non Urgent Maintenance	0 < X < 10 Hrs	Immediate component/mating part degradation	Orange
	Critical <u>or</u> Mission Aborting Failure Mode: Lack of Functionality Results in a RED X*	Maintain Immediately	None	Heavy Metal contamination resulting in Catastrophic Potential	Red

* As defined in DA PAM 738-751 1-Oct-10

Figure 9 ADS-79 Score Card for TDA grading

Although three AGB TDAs were performed as part of this process, the data from the first, removed from 92-26443 in 2005, was invalid due to software changes. Two subsequent removals, from 90-26272 and 92-26454 had valid data and TDAs performed. The thresholds developed from these two were used to diagnose a fourth AGB, also on 92-26454. Damage type and extent was very similar on all three documented AGBs. A TDA was not performed on the fourth, although metal shavings were observed inside the AGB by the maintainers.

92-26443

The gearbox was removed after having experienced three chip events within the last 25 flight hours. Significant ball and raceway spalling was found in the generator drive ball bearings. The envelope demodulation based CIs were responsive to the presence of the fault, however a software change makes the data from this case invalid. The software change only has implications for results prior to December 2005 and thus all other cases presented here utilize the same normalization factors.

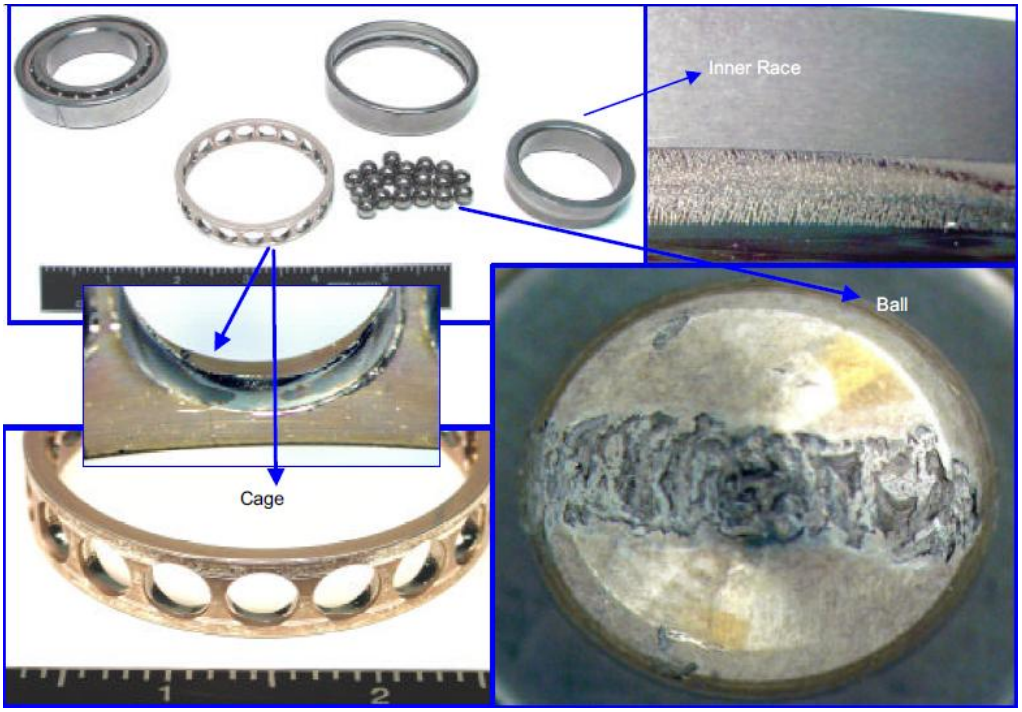

Figure 10 Images from 92-26443 TDA

92-26454

This AGB was removed for excessive chip events. Severe spalling and particle damage was noted on the races and balls. Cage damage was also present. Data from this gearbox was used for thresholding.

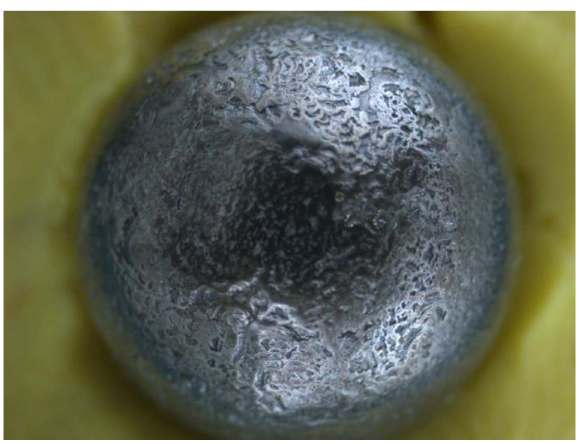
Figure 11 Ball Damage from 92-26454

90-26272

This AGB was removed due to excessive chip events. Roughness and binding of the generator drive ball bearing set was noted in the TDA. Severe spalling and hard particle damage was observed on the races and on the balls. Data from this gearbox was used for thresholding.

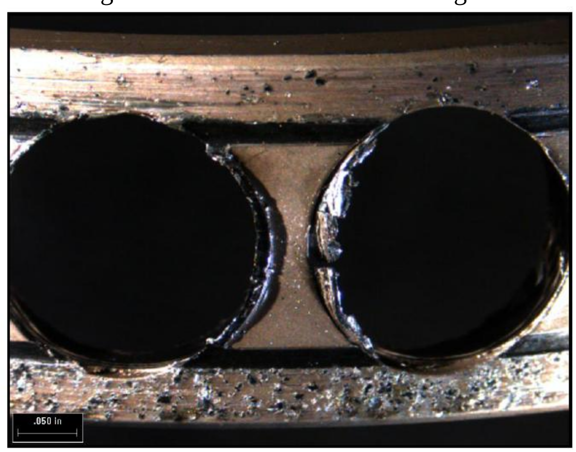

Figure 12 Cage Damage on 90-26272

92-26454 #2

The thresholds obtained from the earlier AGBs were applied to the fleet. A second AGB from 92-26454 was over the newly established limits. The unit, deployed at a forward operating base in Afghanistan, was contacted by the CBM working group. Upon removal of the gearbox, the unit noted metal shavings in the oil. A TDA was not performed on this AGB, and the data is not included in the faulted dataset.

Electronic and Embedded Diagnostics

The IVHMS has built-in accelerometer data quality (DQ) algorithms that check for standard sensor and wiring related faults. When a sensor fails DQ, the data that it collects is only recorded for engineering purposes and is thus masked from the maintainer. DQ fails are triggered by non-zero low frequency intercept, high low frequency slope, clipping, poor signal to noise ratio, and Analog to Digital bit usage.

Conclusion

The authors have demonstrated the process as outlined by ADS-79 for setting the thresholds for vibration diagnostic algorithms. These thresholds are based on the use of tear down analysis and data mining of the UH-60 fleet data. The thresholds are valid for the accessory gearbox drive ball bearing. In the case of this particular bearing, the demodulation enveloping algorithm setup that was assumed during the development of the diagnostics was correct and additional refinement is not necessary unless future data mining efforts show that the false negative or false positive rates increase from the current levels. The ADS-79 core digital source collector attributes of Detectability, Accuracy, Identifiability, and Seperability for the bearing failures has been demonstrated. This threshold setting process has resulted in the capability of the IVHMS to successfully predict accessory gearbox chip events on board the aircraft.

APPENDIX A: ACRONYMS

ADS	Aeronautical Design Standard
AED	Aviation Engineering Directorate
AGB	Accessory Gearbox
BIT	Built In Test
CBM	Condition Based Maintenance
CI	Condition Indicator
DQ	Data Quality
DSC	Digital Source Collector
HI	Health Indicator
IVHMS	Integrated Vehicle Health Management System
ROC	Receiver Operating Characteristic
RUL	Remaining Useful Life
TDA	Teardown Analysis

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