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A Survey of Current Rotorcraft Propulsion Health Monitoring Technologies

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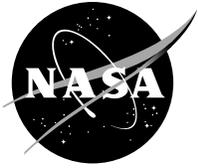
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Abstract

A brief review is presented on the state-of-the-art in rotorcraft engine health monitoring technologies including summaries on current practices in the area of sensors, data acquisition, monitoring and analysis. Also, presented are guidelines for verification and validation of Health Usage Monitoring System (HUMS) and specifically for maintenance credits to extend part life. Finally, a number of new efforts in HUMS are summarized as well as lessons learned and future challenges. In particular, gaps are identified to supporting maintenance credits to extend rotorcraft engine part life. A number of data sources were consulted and include results from a survey from the HUMS community, Society of Automotive Engineers (SAE) documents, American Helicopter Society (AHS) papers, as well as references from Defence Science & Technology Organization (DSTO), Civil Aviation Authority (CAA), and Federal Aviation Administration (FAA).

Nomenclature

AE	Acoustic Emissions
AI	Artificial Intelligence
AHS	American Helicopter Society
CAA	Civil Aviation Authority
CAP	Civil Aviation Publication
CBM	Condition-Based Maintenance
CI	Condition Indicator
DSTO	Defence Science & Technology Organization
FAA	Federal Aviation Administration
FADEC	Full-Authority Digital Electronic Control
HUMS	Health Usage Monitoring System
ICA	Instructions for Continued Airworthiness
IMDS	Integrated Mechanical Diagnostic System
IVHMS	Integrated Vehicle Health Management System
JTFA	Joint Time Frequency Analysis
LTFC	Life-to-First-Crack
LUI	Life Usage Index
MFOQA	Military Flight Operations Quality Assurance
nRTDA	near Real-Time Damage Assessment
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
OSST	Operations Support & Sustainment Technologies Program (U.S. Army)

PDBM	Prognostics Diagnostics Based Management
RFC	Retirement-for-Cause
RUL	Remaining Useful Life
SAE	Society of Automotive Engineers
TBO	Time-Between-Overhaul
TDA	Tear-Down Analysis
VHM	Vibration Health Monitoring

Introduction

The benefits realized or to be realized from rotorcraft propulsion health management have been well documented over the past several decades. This includes maximizing the utilization of the aircraft and/or fleet through improved maintenance planning and practices and the optimal use of spare parts. Also, aircraft safety is improved through health monitoring of flight critical components such as life-limited engine parts as well as gearbox and drive train components for helicopters (Ref. 1). Approaches to health usage monitoring of rotorcraft propulsion systems have evolved from monitoring of engine cycles to predicting individual part failures. Figure 1 details this progression in fidelity in engine health monitoring from the 1970s through the 2000+ time frame (Ref. 2). Figure 2 provides another perspective on the health monitoring of components from simple corrective maintenance (e.g., breakdown maintenance) and preventative or scheduled maintenance to predictive (e.g., condition-based) and proactive maintenance (e.g., prognostics) (Ref. 3). Regardless of the health monitoring approach to rotorcraft engines, improved airworthiness or safety, increased readiness or availability, reduced maintenance tasks, and reduced cost are the major objectives that govern the choice of a specific HUMS methodology (Refs. 1, 4, 5, and 6). Engine size and use also influence the implementation of HUMS. Rotorcraft's smaller turboshaft engines, Figures 3 and 4, as compared to fixed-wing turboshaft engines translates to smaller components (e.g., air foils) with corresponding lower core air flows (10s of lb/sec compared to 100s of lb/sec). However, clearances are proportionally larger thus reducing efficiency and range or payload (Ref. 7). Moreover, rotorcraft are used in more hazardous, harsh, and taxing environments such as the current military operations in the Middle East (Ref. 8). Resultant rapid engine degradation forces operators to push rotorcraft engine limits to obtain the same performance level thus subjecting the engine to higher thermal stresses (Ref. 9). Other special considerations for rotorcraft engines include the following (Ref. 4):

- Torque-matching of engine power outputs to protect helicopter gearboxes;
- Multiple engine control system adjustment to ensure that one engine does not use excessive life, compared to the others;
- The “automatic” engine throttle movements resulting from Power Turbine Governor system operation, to keep the helicopter rotor speed constant despite collective and cyclic pitch inputs from the pilot.

Thus, tools are required that are specific to health and usage monitoring systems of rotorcraft engines. This paper's objectives are the following:

1. Provide the current state-of-the-art in sensors, algorithms, diagnostics, and prognostic tools installed in rotorcraft engines.
2. Identify gaps to support validation and demonstration of HUMS for rotorcraft engine component maintenance credits.

In support of these objectives, a survey (Appendix A) was sent to a small cross-section of the HUMS community to determine the current state-of-the-art in sensors, diagnostics/prognostic tools, and HUMS methodology, validation and effectiveness. The group included engine manufacturers, helicopter manufacturers, HUMS manufacturers, and HUMS users including the U.S. Army and the U.S. Navy. Results of that survey are presented in the appropriate section and are marked as Personal Interview in the endnotes. Also included are findings from the Army's Operations Support & Sustainment Technologies (OSST) Program (Refs. 10 to 13). Finally, a literature search was conducted with references from SAE, DSTO, NATO, NASA, FAA, Army, and AHS proceedings. The FAA provides general guidelines on maintenance credits to extend TBOs for helicopter propulsion systems using HUMS. The SAE documents provide more general guidelines and recommended practices on HUMS. In addition, a number of studies on the state-of-the-art in HUMS were conducted by DSTO, NATO, and NASA and are referenced appropriately below. This paper will cover current standard practices (i.e., philosophies, sensors, data acquisition and data transfer, helicopter engine monitoring and analysis, HUMS guidelines, HUMS verification and validation), new practices, lessons learned, and future challenges.

While an effort was made to include references from as wide a range of sources as possible, the included bibliography is not exhaustive and therefore the paper should be treated as a work in progress as this is a dynamic environment with more rotorcraft being equipped with HUMS every year. The data is considered to be current per the publication date of this document. Also, a significant number of references are taken from SAE, AHS, DoD, and FAA sources and as such the findings may be geared more towards U.S. health usage monitoring systems. Finally, this paper is limited in scope to the following dynamic mechanical components for rotorcraft engines. This would include blades/vanes, disks, spacers, shafts, bearings, combustors, gears, and rotating seals (Ref. 4). Engine health monitoring via gas path analysis or other conventional engine performance parameters is not treated in this paper. For additional information in this area, the reader is pointed towards a number of references (e.g., NASA/TM—2004-213202, NASA/TM—2005-213622) as a starting point.

Standard Practices

Philosophies

As shown in Figure 2, health monitoring methodologies are evolving from preventative type maintenance (i.e., Hard-time, Time-Between-Overhaul (TBO), Retirement-for-Cause (RFC), Damage Tolerance) to achieving more Predictive and Prognostic type methods (e.g., on-condition). Preventative-type maintenance or scheduled maintenance is usually based on part history or via elapsed time in use. Both predictive and proactive maintenance strategies attempt to extend component time on wing. While predictive maintenance seeks to replace components based on part condition through observation or through analysis of sensor readings, proactive maintenance seeks to replace parts based on predictive analyses. These analyses, in turn, may be based in part on sensor data. Part of the U.S. Army's Condition-Based Maintenance (CBM) program attempts to extend time on wing through improved life prediction methodologies, multi-sensor data fusion, and intelligent reasoning and control (Ref. 3). The U.S. Army's ultimate goal is to have component replacement "on-condition". Regardless of the health monitoring methodology, these maintenance strategies fit within an engine health monitoring framework. SAE ARP 1587B provides an excellent example via a block diagram of a typical EHM architecture where the HUMS information flow path (e.g., sense-acquire-transfer-analyze-act) can be deduced (Ref. 1).

Sensors

Existing sensors on helicopter engines provide operational assessments on engine performance (e.g., exceedance monitoring, RUL, gas path diagnostics, and maximum power assessments). The gas turbine engine's control system, or Full-Authority Digital Electronic Control (FADEC), contains codes which on modern platforms can provide independent checks on the health of the helicopter engines and their

subsystems (Ref. 14). A subset of these sensors are used for fault detection including accelerometers (vibration monitoring), oil debris monitors (component degradation), and thermocouples (exceedance monitoring). Guidelines of actual sensor specifications such as accuracy, resolution, sampling rate, etc. are platform/mission specific (Refs. 4, 15, 16, and 17). For example, U.S. Army document ADS-79B-HDBK provides typical sensor accuracy and resolution requirements, Table 1 (Ref. 2). Table 2 provides additional references on typical specifications for accelerometers, rotational sensors, temperature sensors, and oil monitoring devices. Finally, depending upon the type of monitoring function (e.g., Limit/Exceedance, Life Usage, mechanical trending, mechanical diagnosis) a number of engine measurement parameters may be useful. SAE AIR 4061B provides a matrix of typical engine parameter data used with respect to their monitoring function. Parameters include temperature, pressure, thrust, vibration, and oil particle count (Ref. 18).

Data Acquisition and Data Transfer

The process of acquiring data from the various engine sensors and transferring it to a ground station for analysis is accomplished through a variety of methods. The process involves the capture, extraction, processing, and analysis of HUMS data through manual methods (e.g., hand-carried, ground-station, equipment, physical media), automated methods (e.g., satellite, radio, wireless), or combinations of both. The degree of automation is partially driven by the processing and analytical capabilities of the specific engine HUMS (Ref. 1). Typically, more detailed or computer intensive analyses are carried out off-board due to limited on-board memory and processor capacity (Ref. 19). Data bus standards such as ARINC 429, ARINC 717, and Mil-Std-1553 are noted here as standard communication protocols for commercial and military helicopters, respectively. SAE AS 5395 provides guidelines for HUMS data format interchange within an open system architecture. Example HUMS include Honeywell's 1239 (Ref. 20) system and Goodrich's IVHMS system (Ref. 21). Current challenges include ensuring data accuracy, integrity, and reliability through the data acquisition and transfer process (Refs. 16 and 22). Decreasing the time from data acquisition to on-board or ground station analysis would increase the effectiveness of the HUMS in alerting operators of any engine maintenance issues. Thus, areas for improvement would be in increasing the reliability of on-board analyses and increasing on-board data storage and throughput while preserving data integrity and quality (Ref. 1).

Helicopter Engine Monitoring and Analysis

The objective of helicopter engine health monitoring is to reliably determine the condition of the engine and its components and to give an indication of any maintenance required. Traditional methodologies such as cycle counting, vibration monitoring, and oil debris monitoring are currently used but sometimes require a prohibitive amount of on-board computer resources (e.g., memory, storage, processor speed). Thus, one challenge is to balance on-board health and usage monitoring techniques such as trending, cycle counts, and condition indicators with available on-board computer resources. Another challenge is to reduce the time period from acquisition of the health monitored data and its subsequent analysis to resultant maintenance actions, if any, for the helicopter engine.

The goal of vibration analysis with respect to helicopter engine monitoring is to accurately assess the operational condition of rotating parts (e.g., seals, bearings, gears, blades, etc.) and to give sufficient warning of impending part failure. Rotating parts exhibit natural frequencies which change as the part condition begins to deteriorate. These changes may be observed by the presence and relative amplitude of characteristic harmonics and sidebands. The detection of these frequencies of interest is complicated by a number of factors including the sensor location relative to the rotating component of interest as well as the presence of natural frequencies in the vibration signature of other nearby rotating components. Thus, the challenge is to separate the frequencies of interest and accurately determine if maintenance is required on the rotating component. Analysis techniques can be broadly grouped into either time domain analyses (e.g., Root Mean Square, Crest Factor) or frequency domain analyses (e.g., filtering, FFT, Cepstrum,

order tracking) (Ref. 23). Also, because of the large amount of data required for vibration analysis an additional challenge, as mentioned previously, is to determine the state of the component with limited on-board snapshot data.

Similar to vibration analysis, oil debris monitoring seeks to quantify part wear (e.g., oil-wetted bearings and gears) due to the detection and identification of debris in the helicopter engine oil system. Chip detectors and their corresponding algorithms are used on-board to indicate oil system debris levels as well as threshold alarms. Example chip detectors and systems include GasTops MetalSCAN, (Ref. 24) Vibro-Meter's chip detector system, (Ref. 25) or Eaton's debris monitoring system (Ref. 26). As with vibration monitoring, oil debris monitoring alarm levels are worked closely between the manufacturer and user. Off-board analyses may include classification, troubleshooting, spectrography, spectrophotometry, or scanning electron microscopy (Ref. 27). Regardless of technique, reliability and accuracy of the data and timeliness of any maintenance action are key for successful oil debris monitoring.

The objective of life usage monitoring of life-limited parts (e.g., blades, disks) is to safely and reliably predict part remaining useful life (RUL). Two traditional approaches are the safe-life approach and damage tolerance approach. The safe-life approach, based primarily on low-cycle fatigue criteria, determines part life based on when cracks begin to form on components. Alternatively, the damage tolerance approach, based on fracture mechanics, determines the critical crack-length to failure of the component. Safe-life methodologies include Rainflow (Ref. 16), and life-to-first crack or LTFC (Ref. 4). Damage tolerance methods include RFC and 2/3 dysfunction life (Ref. 4). Also, thermal fatigue and creep are considered as well for life-limited components (Ref. 16). Finally, guidelines on the logistics of tracking life-limited parts are outlined in SAE AIR 1872 Rev. A (Ref. 16).

On-board condition indicators (CI) commonly found in HUMS boxes as mentioned in the Sensors section, provide alert levels (e.g., hi/lo temperature, vibration, pressure, etc.) and are recorded and analyzed using a number of techniques as previously described. The U.S. Army's ADS-79B-HDBK document provides methods on developing and validating CIs (Ref. 2). Again, CI thresholds and alert levels are platform specific, and thus are developed closely between the HUMS supplier and user (Ref. 28).

HUMS Guidelines

A number of organizations have provided guidelines for HUMS relating to overall philosophy, sensor specifications, installation, and lessons learned. The Society of Automotive Engineers (SAE) provides a number of these documents. A listing is shown in Appendix B. In 1999, the U.K.'s Civil Aviation Authority (CAA) published Civil Aviation Publication (CAP) 693 (Ref. 29) that provides operators with guidelines for installation and use of health monitoring systems. The CAP described the level of monitoring required and provided advice on ensuring that the monitoring was effective and reliable. In 2006, the CAA published the document CAP 753, (Ref. 30) which provides additional guidance to operators using vibration health monitoring (VHM) in helicopter rotor and drive systems. In this document they define VHM as, "the monitoring of vibration data and characteristics that can provide advance information relating to the development of incipient failures in the engine(s) rotor drive systems (Ref. 30)".

Also, in 1999 the FAA published Advisory Circular (AC) 29-2C MG 15, Airworthiness Approval of Rotorcraft Health Usage Monitoring Systems (HUMS), which provides guidance to achieve airworthiness approval for HUMS installation, credit validation, and Instructions for Continued Airworthiness (ICA) for the full range of HUMS applications (Ref. 31). An economic benefit in following AC 29-2C MG 15 is that it allows the operator to inspect and remove components based on HUMS indications instead of scheduled maintenance intervals for specific components. To receive maintenance credits so as to increase the service life of a specific component, the HUMS application for which credits are sought must be validated. Evidence must be provided in the form of seeded fault tests and/or fielded data that demonstrate the HUMS responds to the specific component fault with appropriate alert limits. Seeded

fault testing refers to the process of initiating a defect in a component and monitoring the progression of the defect with health monitoring equipment.

The U.S. Army is also in the process of providing guidelines (ADS-79B) on obtaining maintenance credits for its fleet of helicopters.

Verification and Validation of HUMS

Verification and validation of HUMS is critical in providing the necessary evidence that justifies the use of these systems in making decisions for safety critical maintenance items on not only helicopter engine components but the drive, structural, and rotor systems as well. The FAA and U.S. Army define Verification and Validation as follows:

FAA Definition per FAA VVSPAT-A2-PDD-014 (Ref. 32)

“Verification.—Confirmation that selected work products meets their specified requirements. This includes verification of the end product (system, service or operational change) and intermediate work products against all applicable requirements. Verification is inherently an incremental process since it occurs throughout the development of the end product and work products, beginning with initial requirements, progressing through subsequent changes, and culminating in verification of the completed end product.

Validation.—Confirmation that an end product or end product component will fulfill its intended purpose when placed in its intended environment. The methods employed to accomplish validation are applied to selected work products as well as to the end product and end product components. The work products should be selected on the basis of which are the best predictors of how well the end product and end product component will satisfy the intended purpose and user needs. Validation may address all aspects of an end product in any of its intended environments, such as operation, training, manufacturing, maintenance, or support services.”

U.S. Army Definition per ADS-79X-HDBK-Appendix VV Rev 090110 (Ref. 33)

“Verification.—Confirms that a system element meets design-to or build-to specifications.

Throughout the systems life cycle, design solutions at all levels of the physical architecture are verified through a cost-effective combination of analysis, examination, demonstration, and testing, all of which can be aided by modeling and simulation.

Validation.—The process of evaluating a system or software component during, or at the end of, the development process to determine whether it satisfies specified requirements.”

Thus verification and validation are complimentary activities that require confirmation that the HUMS functions as specified at key points (i.e., component versus system level) during the development and test phase of the system. End-to-end testing, verification that the system operates in “all foreseeable circumstances”, verification and validation of both software, hardware, and data transfer, an understanding of known deficiencies, and use of an appropriate approval authority are also key to these two activities (Ref. 4). SAE AIR 5120 provides specific guidance on a tiered verification process involving simulation and Rig/Bench testing through Static Aircraft, Engine, and Flight Testing (Ref. 22). Finally, SAE AIR 1872 details validation of life usage algorithms at both the algorithm level and system level. The importance of a large database for correlation is discussed as well as acceptable deviations between computer simulation and system level checks (Ref. 16). The U.S. Army’s CBM program is currently validating HUMS through case studies and seeded fault testing (Ref. 28), as well as validation of vibration algorithms performance via tear-down analyses (TDAs) of faulted components (Ref. 34). The U.S. Army’s V&V process, particularly for maintenance credit, is further detailed by Menon and others (Ref. 35). Prior to an end-to-end verification process the document stresses the importance of having a HUMS that is controlled with known configurations for all HUMS elements. Validation metrics are suggested as well as methods to address data uncertainties, variability, and sample sizes. Examples are

given including bearing health monitoring. Also, methodologies to quantify vibration algorithm performance are presented in SAE ARP 5783 (Ref. 36). Finally, a method for quantifying engine monitoring system performance is given in SAE AIR 4985 (Ref. 37).

New Practices for Engine Health Monitoring Systems

In considering new maintenance practices pertaining to HUMS for helicopter engines it is useful to consider the following guidelines from Rickmeyer and Dempsey (Ref. 38):

1. "...any maintenance enhancement, modification, or replacement should be verified and validated as good as, or better than, legacy maintenance practices."
2. "...any maintenance system proposed to replace legacy inspections and overhaul intervals should undergo similar scrutiny to demonstrate sufficient engineering rigor and robust design."
3. "The ultimate goal of rotorcraft health management systems for dynamic propulsion components is to achieve true "on condition" based maintenance and operational quality while increasing the safety of rotorcraft."

In addition, cost of implementation would be another factor in considering changes to existing maintenance practices for rotorcraft engines. In recent years, a number of promising developments in engine health monitoring have begun to address current maintenance practices in an effort to achieve true "on condition" based maintenance. A number of these efforts are highlighted below.

1. Results from the Army's OSST program show promise in fusing vibration and oil-debris monitoring bearing data to provide earlier indications of impending bearing failure as compared to traditional condition indicators. Honeywell's CBM program has demonstrated in seeded bearing tests in both rig and engine testing the validity of a two-stage fusion approach. Further, a damage milestone (DM) progression methodology is introduced based on bearing geometry and appears to provide a more "robust" indication of bearing failure (Ref. 10). Other OSST technologies developed and/or demonstrated included erosion detection, continuous power assurance, model-based torque prediction, RUL, and power management. The RUL module uses a neural network approach to predict disk temperatures and stresses which are then fed into life prediction algorithms in order to calculate the remaining useful life (Refs. 11 to 13).
2. In an effort to reduce operating costs, increase operational availability, and reduce maintenance burden, a Regime Recognition system has undergone a initial successful flight test on-board an EC135. Determination of the actual mission profile and thus the true load spectrum would enhance dynamic component life monitoring (Ref. 39).
3. The US Navy has begun implementation of automated rotorcraft engine power checks on-board the CH/MH-53E which has the GE-64 turboshaft engine. Also part of the Prognostics Diagnostics Based Management (PDBM) program, the Navy has also begun demonstration of an engine torque performance algorithm as a life assessment module incorporating Life Usage Indices (LUIs) and near Real Time Damage Assessments (nRTDAs). Demonstration of these modules was scheduled to begin in early 2011 (Ref. 40).
4. A small business has developed a bearing corrosion detection methodology based on joint time-frequency analysis (JTFA) that shows, from initial seeded fault rig testing and analysis, the potential ease and accuracy of quantifying corrosion level severity (Ref. 41).
5. SAE AIR 1828 RevB notes in the area of oil debris monitoring the trend towards "finer filtration" (e.g., 3 to 10 μm) and a corresponding increase in sensitivity to spectrometric techniques (e.g., plasma spectrometers) (Ref. 27).
6. The Department of the Navy has begun instituting a knowledge management process known as Military Flight Operations Quality Assurance (MFOQA) for its Integrated Mechanical Diagnostic Systems (IMDS). The goal of MFOQA is "to provide objective and actionable information that can

be used to reduce flight related risks and improve aircrew training, maintenance, and operational efficiencies.” The paper referenced here reveals trends and patterns on rotorcraft usage across a fleet of helicopters based on IMDS events (e.g., exceedance, flight hours, autorotation) (Ref. 42).

Lessons Learned

Given health usage monitoring of rotorcraft engines’ familiar objectives of improved readiness, increased airworthiness, reduced maintenance, and reduced costs, a common HUMS philosophy is the trend towards true on-condition monitoring—a HUMS research area identified previously by Fraser in 1994 having potential for substantial cost benefits (Ref. 6). Considering the various R&D efforts working towards this goal, a number of lessons learned have been documented in the literature—a number of which focus on the areas of data integrity, information management, and communication. Following is a brief summary of these three areas.

Maintaining data integrity (e.g., accuracy, resolution, robustness) through the HUMS data flow process (e.g., sense-acquire-transfer-analyze-act) is a continuous challenge through the research, development, and validation of HUMS and their subsystems. High false alarm rates have been reported in the literature (Refs. 19 and 43). Causes for these alarms stem potentially from faulty sensors or CIs, limited field data to validate the CI, or an incomplete understanding of damage progression levels (e.g., bearing damage progression) (Ref. 38). With limited on-board data storage capacity it is suggested that hybrid models (physics-based and empirical models) may offer a solution that addresses concerns for accuracy, ease of development, and maintenance (Ref. 19).

With increasing quantities of data for analysis from HUMS (vibration, oil debris, etc.), strategies to manage the information flow path are vital for success (Ref. 19). This area of needed research was also identified by Fraser in 1994 and includes elements that are being instituted or worked on today (Ref. 6):

- Automatic scheduling of the application of health and usage algorithms.
- Combining the results of different forms of analysis (e.g., vibration and oil debris analysis).
- Coordinating and presenting maintenance advice.
- Screening and taking account of bad data, and flagging monitoring system faults.
- Parts life tracking and interfacing with logistics management schemes.
- Automatic processing of other data.
- Archiving of selected data.
- Coordinating and maintaining fleet status records.

Modularity, efficiency, and timeliness in the information management process would also support increased rotorcraft airworthiness and availability. Alternatively, a “sluggish” process could potentially lead to maintenance “shortcuts” or “neglect” (Ref. 19). Also, differences in rotorcraft usage (e.g., desert, city, training) require a finer knowledge management process as given by example in the previous section by the Department of the Navy’s MFOQA program.

Finally, the need for continuous and clear communication is essential for both users and suppliers of HUMS, engines, and airframe manufacturers throughout the design, development, and implementation of the HUMS (Refs. 4 and 15). From developing specifications and tailoring existing systems or developing new subsystems to fit within user parameters to finally validating the system as a whole requires constant lines of communication, preferably early in the process (Ref. 19). SAE AIR 1871C provides a number of lessons learned on HUMS for both propulsion as well as drive train systems.

Future Challenges

Improvements for HUMS for rotorcraft engines are identified and grouped in terms of management, sensors, and analysis. Management of HUMS programs and information will be necessary in working towards true on-condition monitoring. Effecting worthwhile change in current engine monitoring methods will require insight and understanding of the level of robustness and engineering rigor required to maintain safety and airworthiness standards (Ref. 38). For users (individual and small market) without the resources to pull data off the aircraft and transfer it for analysis, the ability to download data without intervention would make it possible to monitor engines post-flight and track operation (Ref. 44). In terms of extending TBOs for rotorcraft engines, Rickmeyer and Dempsey, suggest a number of methods (Ref. 38):

- TBO extension based on field experience but limited to current calculated part lives.
- Instituting a reliability-based approach to validating a HUMS with statistical rigor.
- Redesign and requalify legacy TBO components to extend TBO.

Simon and others point out a number of needed engine sensor improvements in vibration (50 kHz bandwidth), oil debris (non-magnetic debris detection in the 125 to 700 μm range), oil quality (real-time measurement), blade health (300 g vib, 100 to 500 kHz bandwidth), prognostics (2000 °F metal temperature measurement), and NDE (wireless eddy-current). Also, “for production engine applications, these sensors need to be affordable, reliable, light-weight, and be readily installable and accessible.” The report also alludes to virtual sensors via “indirect measurement techniques” (Ref. 45). Also, embedded sensors (Ref. 28) in combination with wireless technology in engine components could potentially streamline the acquisition of HUMS data as well as eliminate issues involved with cabling and optimizing sensor location.

There is a continuous challenge to improve the reliability and confidence levels of an algorithm, condition indicator, analytical method, or the HUMS as a whole especially for obtaining maintenance credits. Statistical methods are currently being investigated for HUMS for rotorcraft engines. Sapsard provides some initial statistical guidance on the number of engines (or engine components) to monitor in a fleet (Ref. 4). Rickmeyer and Dempsey include hypothesis testing as well as sample size determination for reliability, demonstration and testing of a CI to detect a component fault (Ref. 38). Also, ASTM E 122-09 provides general guidance on calculating sample size (Ref. 46). Finally, MIL-HDBK-781A gives guidance on test plans, test methods, and environmental profiles for reliability testing of systems and equipment (Ref. 47). These sources also implicitly state a requirement of technical or expert background regarding the potential sources of faults in the system (e.g., rotorcraft engine) such that the statistical techniques are used in a judicious manner.

Data fusion shows promising results as given by the OSST example discussed above (e.g., fusion of vibration and oil debris monitoring data). Acoustic emissions (AE) sensing is another potential research area for HUMS for rotorcraft engines. Case studies in the drive train area (e.g., gears) are currently being investigated by He and others. AE has been used extensively for non-destructive evaluation of materials for cracks and has shown an insensitivity to background noise in rotating machinery as well as sensitivity to faults and their locations (Ref. 48). Other areas of potential research include artificial intelligence (AI) monitoring techniques such as neural networks and fuzzy logic with the potential advantage of learned automated fault detection in rotorcraft engines.

Other needed advancements for rotorcraft engine HUMS include diagnostic tools for isolating faulted hardware and trending conditions. Also, needed would be real time life usage recognition and performance tracking of engine health and mission planning capabilities to reduce maintenance test flights to determine the same (Ref. 34).

Beyond post flight and real-time analysis, prognostic methods would be needed to advance HUMS for engines towards true on-condition monitoring. The inherent nature of these predictive methodologies would necessitate a solid statistical and technical basis to ensure accuracy. Benefits would include

reduced reliance on manual checks and inspections as well as improved flight safety, improved operational availability, reduced life cycle costs, optimized maintenance/inspection intervals (Refs. 1 and 49). Prognostic approaches may include experienced-based, evolutionary, feature progression, AI-based, state estimator, and physics-based (Ref. 49).

Identified Gaps

A number of gaps have been identified that may complicate the implementation of maintenance credits to extend part life for rotorcraft engines. While not an exhaustive list, the gaps identified in this research are centered from the viewpoint that HUMS technology have been developed for specific engines, platforms, missions, etc. This would include sensor and their locations on engines, the CIs developed and their associated alert levels, the means of acquiring the data and transferring it to ground station in a timely manner, and finally, acquiring a sufficient data set for accurate analysis. Certainly, the development of HUMS technology in terms of accuracy and robustness is of primary concern for accurately assessing the condition of rotorcraft engine health. However, to extend part life through the use of maintenance credits would require greater consistency in the use of HUMS technology, possibly at the fleet/mission level if not higher. Also, CI maturity in terms of accuracy and robustness will need to be improved to reduce false alarm rates to acceptable levels. Finally, the need for efficient management of HUMS data as well as continued consistent and clear communication between HUMS users/suppliers from Depot to management level will be necessary to successfully implement the maintenance credit process in both the civil and military rotorcraft engine environment.

Conclusions

A brief review on the state-of-the-art in HUMS technology was conducted for rotorcraft engines. Survey feedback from the HUMS community, a review of the literature, and a review of HUMS guidelines (SAE, DoD, etc.) have resulted in a number of observations. A number of collaborative efforts between HUMS users and suppliers appear to have shown promise in furthering HUMS technology. One example is fusing bearing and vibration data to determine impending part failure (e.g., OSST program). Another example is increasing the fidelity of determining part life by an automated regime recognition program (e.g., EC135). In general, the application of any HUMS technology to existing rotorcraft engines is highly specific to platform and mission. Close collaboration between users and suppliers is critical to the successful implementation of the technology, particularly in the case where Maintenance Credits are being sought by users from the various governing bodies (e.g., FAA, CAA). As always, airworthiness, readiness, and availability will remain uncompromised. Also, statistical rigor, accuracy of data, reduction of false alarms, and data integrity are key to further development of analytical tools, CIs, HIs, etc. Research efforts and developments in the area of prognostics will be increasingly important in realizing true on-condition monitoring. Finally, timeliness of maintenance actions will also be a factor to the success of any HUMS program.

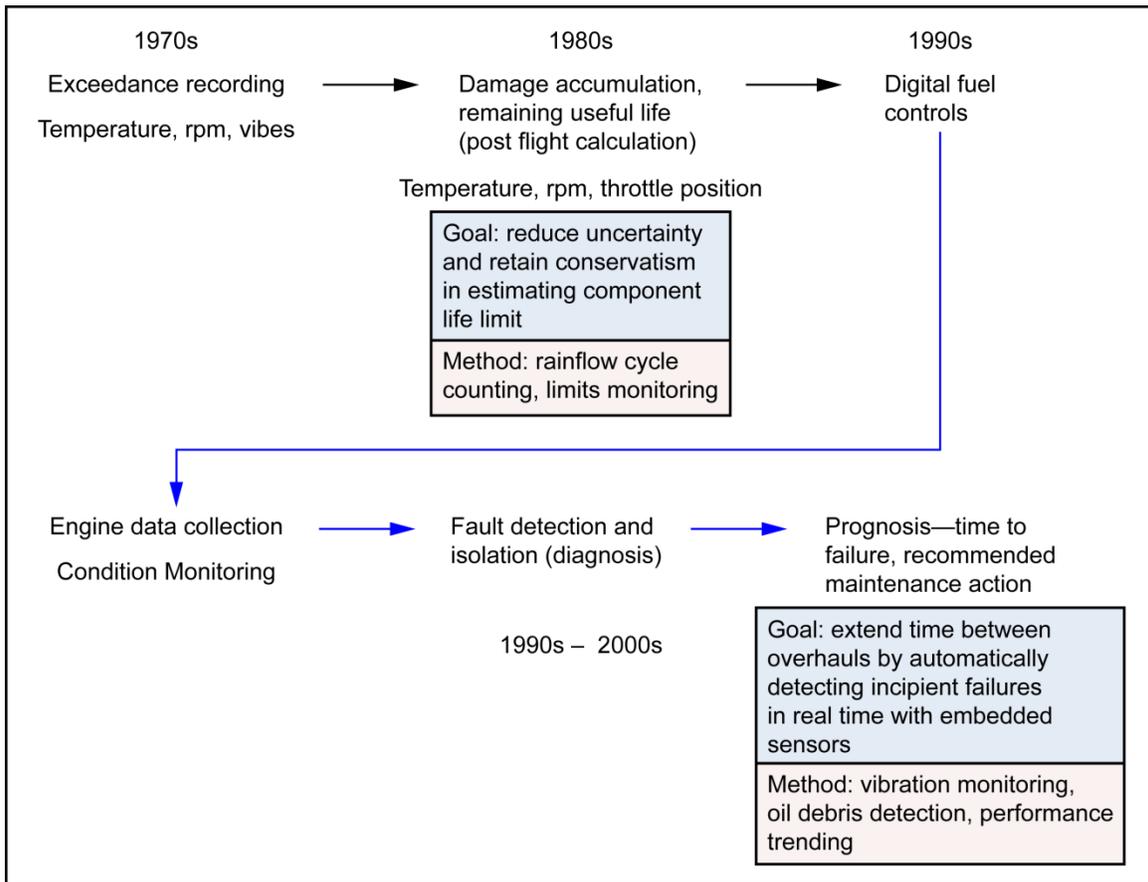


Figure 1.—Progression of turbine engine monitoring technology (Ref. 2).

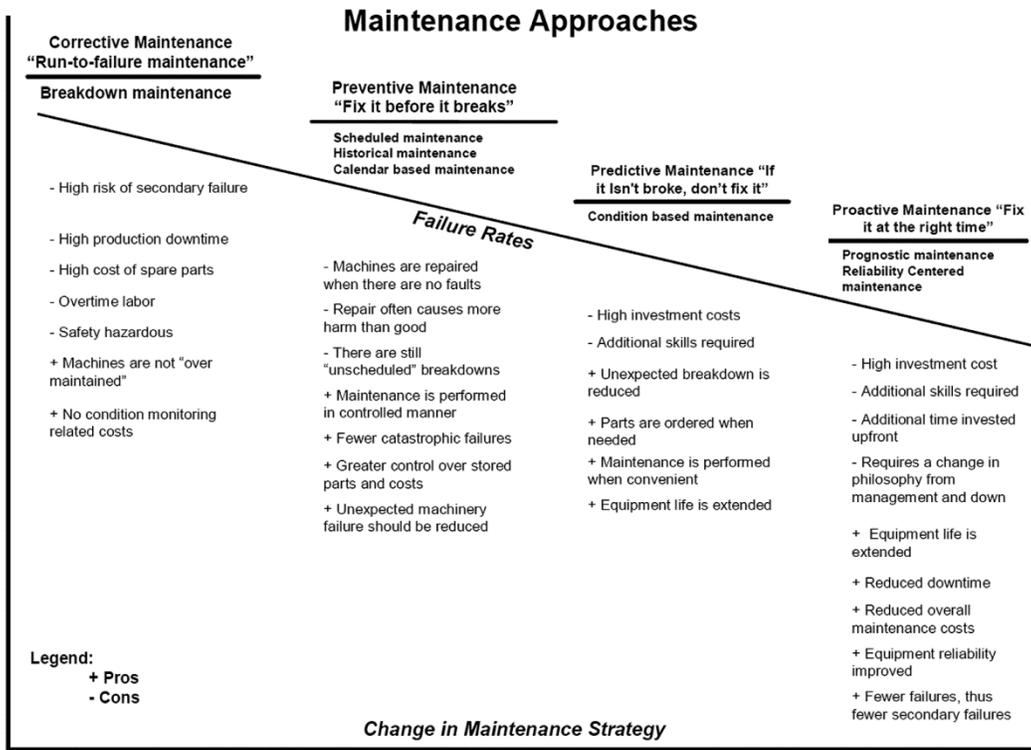


Figure 2.—CBM maintenance approaches per CBM+ DoD guidebook (Ref. 3).

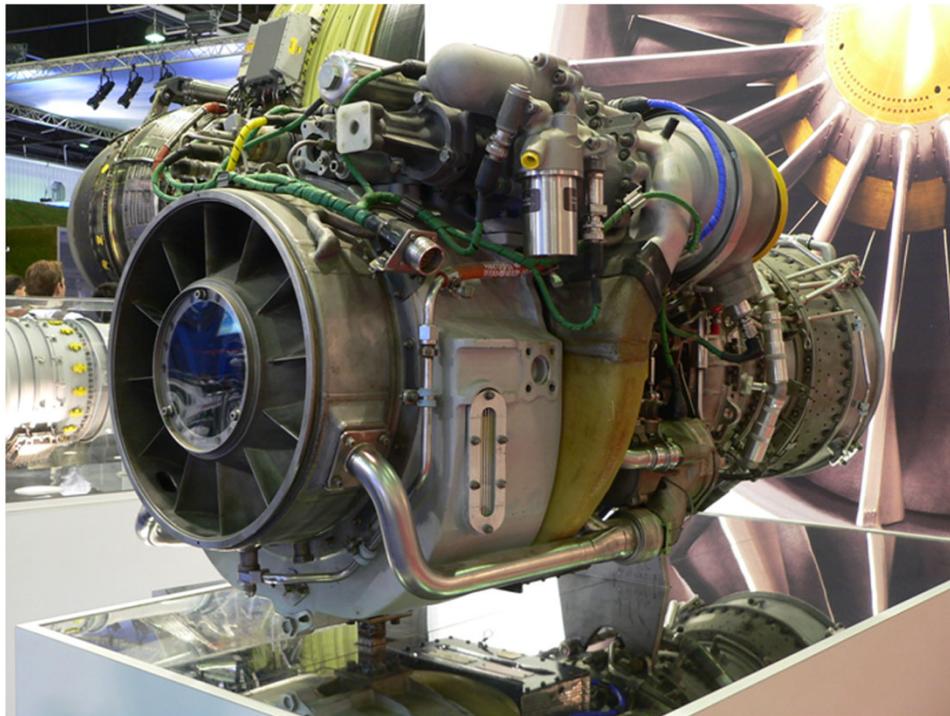


Figure 3.—GE-T700 turboshaft engine (Ref. 2).

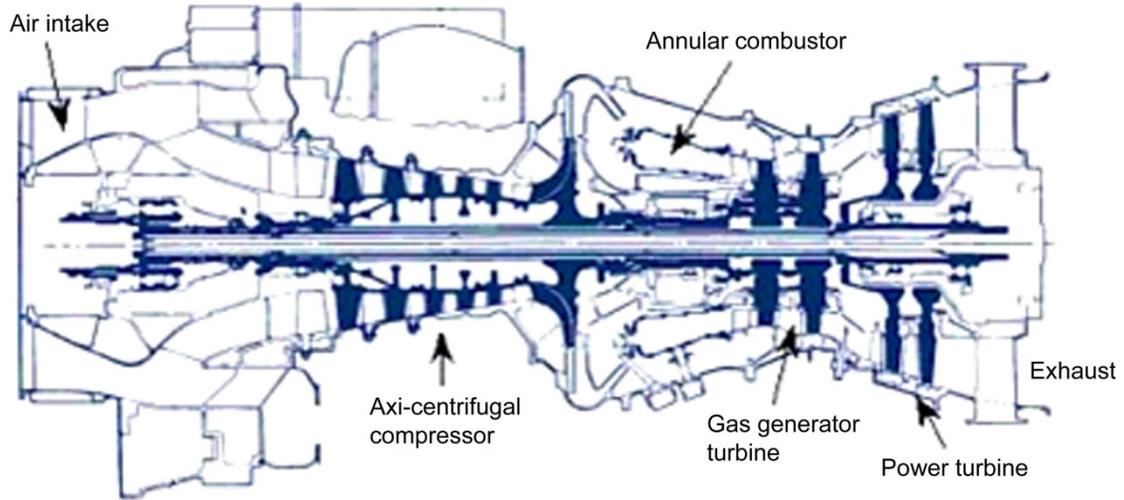


Figure 4.—Schematic of GE-T700 turboshaft engine (Ref. 2).

TABLE 1.—U.S. ARMY SENSOR ACCURACY AND RESOLUTION REQUIREMENTS (REF. 2)

Signal	Accuracy	Resolution
Spool speed	0.1 percent	0.05 percent
Temperature	1.8 °F	0.9 °F
Engine intake	7.2 °F	3.6 °F
Compressor exit	7.2 °F	3.6 °F
Stator outlet	7.2 °F	3.6 °F
Exhaust gas	3.6 °F	1.8 °F
Turbine blade	7.2 °F	3.6 °F
Engine intake pressure	0.290 psi	0.145 psi
Compressor exit pressure	1.45 psi	0.435 psi
Indicated airspeed	2 kts	1 kts
Pressure altitude	100 ft	50 ft
G-load	0.01 g	0.005 g

TABLE 2.—GENERAL SOURCES FOR HELICOPTER ENGINE SENSOR SPECIFICATIONS

Sensor	Source
General	SAE ARP 1217 RevA
Accelerometer	ADS-79B-HDBK, SAE AIR 1839C, SAE AS5391, SAE AS8054
Rotational sensor	SAE AS5392
Temperature	SAE AIR 46B, SAE AIR 1900 RevA, SAE AS8005 RevA
Oil monitoring	SAE AIR 1828 RevB

Appendix A—HUMS Questionnaire

1. What HUMS regulations, recommended practices, or industry standards do you follow? (e.g., FAA, SAE, DoD, internal).
2. Please state any objectives or goals for your engine HUMS program and describe your approach within your maintenance procedures. (e.g., Time-based, conditioned-based monitoring, other)
3. What helicopter platforms do you operate or apply your technology to? (Please provide both helicopter and engine make/model.)
4. Describe your HUMS equipment. If possible, please provide manufacturer, system, sensor, engine measurement parameter, etc. (References, attachments are welcome.)
5. Describe your HUMS information flow path (i.e., sense-acquire-transfer-analyze-act).
6. Describe your HUMS algorithms or condition indicators (CIs) used to determine the health of an engine component.
7. How is your HUMS validated/benchmarked?
8. How effective is your HUMS program? Quantify in terms of reduced operating costs, improved vehicle readiness, or improved safety if possible.
9. What is needed for further advancement of HUMS for helicopter engines? (i.e., Where in your opinion should the next HUMS advancements be in? Diagnostic Tools? Instrumentation? Prognostic Tools?)
10. Open comment. Do you have any other concerns, questions, comments not addressed in the previous questions?

Appendix B—SAE HUMS Related Documents

SAE AIR46	The Preparation and Use of Chromel-Alumel Thermocouples for Aircraft Gas Turbine Engines
SAE AIR1828	(R) Guide to Engine Lubrication System Monitoring
SAE AIR1839C	(R) A Guide to Aircraft Turbine Engine Vibration Monitoring Systems
SAE AIR 1872	Guide to Life Usage Monitoring and Parts Management for Aircraft Gas Turbine Engines
SAE AIR 1873	Guide to Limited Engine Monitoring Systems for Aircraft Gas Turbine Engines
SAE AIR 1900	(R) Guide to Temperature Monitoring in Aircraft Gas Turbine Engines
SAE AIR 4061B	(R) Guidelines for Integrating Typical Engine Health Management Functions Within Aircraft Systems
SAE AIR 4175	(R) A Guide to the Development of a Ground Station for Engine Condition Monitoring
SAE AIR 4176	Cost Versus Benefits of Engine Monitoring Systems
SAE AIR 4985	A Methodology for Quantifying the Performance of an Engine Monitoring System
SAE AIR 4986	Engine Electrostatic Gas Path Monitoring
SAE AIR 5120	Engine Monitoring System Reliability and Validity
SAE AIR 5317	A Guide to APU Health Management
SAE AIR 5871	Prognostics for Gas Turbine Engines
SAE AIR 1871C	(R) Lessons Learned from Developing, Implementing, and Operating a Health Management System for Propulsion and Drive Train Systems
SAE AIR 4174	A Guide to Aircraft Power Train Monitoring
SAE ARP 1217	Instrumentation Requirements for Turboshaft Engine Performance Measurements
SAE ARP 1587B	Aircraft Gas Turbine Engine Health Management System Guide
SAE ARP 5783	Health and Usage Monitoring Metrics Monitoring the Monitor
SAE AS4831	Software Interfaces for Ground-Based Monitoring Systems
SAE AS5391	Health and Usage Monitoring System Accelerometer Interface Specification
SAE AS5392	Health and Usage Monitoring System, Rotational System Indexing Sensor Specification

- SAE AS5393 Health and Usage Monitoring System, Blade Tracker Interface Specification
- SAE AS5394 Health and Usage Monitoring System, Advanced Multipoint Interface Specification
- SAE AS5395 Health and Usage Monitoring System Data Interchange Specification
- SAE AS8005 Minimum Performance Standard Temperature Instruments
- SAE AS8054 Airborne Engine Vibration Monitoring (EVM) System, Guidelines for Performance Standard for

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14. ABSTRACT A brief review is presented on the state-of-the-art in rotorcraft engine health monitoring technologies including summaries on current practices in the area of sensors, data acquisition, monitoring and analysis. Also, presented are guidelines for verification and validation of Health Usage Monitoring System (HUMS) and specifically for maintenance credits to extend part life. Finally, a number of new efforts in HUMS are summarized as well as lessons learned and future challenges. In particular, gaps are identified to supporting maintenance credits to extend rotorcraft engine part life. A number of data sources were consulted and include results from a survey from the HUMS community, Society of Automotive Engineers (SAE) documents, American Helicopter Society (AHS) papers, as well as references from Defence Science & Technology Organization (DSTO), Civil Aviation Authority (CAA), and Federal Aviation Administration (FAA).					
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