Cryocooler Prognostic Health Management System

E. Sandt[1], L. Penswick[1], A. Shah[1], C. Dodson[2] and T. Roberts[2]

[1]Sest, Inc., Middleburg Heights, OH 44130 USA
[2]Air Force Research Laboratory, Kirtland Air Force Base, NM 87117 USA

ABSTRACT

The use of cooled sensors in ever more complex, integrated applications has made determination of the cryocooler and related component "health or remaining reliable useful life" a critical factor in successfully meeting mission requirements. Sest Inc. has been actively developing a Cryocooler Prognostic Health Management System (CPHMS) under U.S. Air Force sponsorship to address this issue. Using non-invasive means to measure performance of a cryocooler with limited data availability, a variety of failure mechanisms have been evaluated based on a combination of "physics of failure" assessments as well as the results of extensive cryocooler testing carried out on "healthy" and selectively "degraded" cryocoolers. Used in conjunction with simple models of the fundamental dynamic behavior of linear drive free-piston systems, it is possible to identify the presence and type of potential degradation mechanisms. For a diagnostic system, identifying that a problem exists is half the battle. In the CPHMS with the results from the earlier diagnostic evaluation available, it is possible to carry out prognostic estimation of the reliable remaining useful life (RRUL) by the use of Bayesian statistics. The latter are used to continuously improve the estimations of RRUL for the cryocooler under various failure modes. While the CPHMS is focused on "tactical" class cryocooler, the basic approach is easily adapted to other cryocooler types, as well as more complex integrated systems.

INTRODUCTION

Aircraft systems flight health monitoring system development has gained increasing momentum in the US Department of Defense and industry owing to its benefits related to mission management, mission success, logistics issues, cost savings, inventory management, maintenance and repair schedules, efficiency, reliability of the systems and missions, etc. Recent technological advancements in computers, information systems, sensors, electronics, wireless communications, avionics, etc. have provided the incentive to the development of more powerful health monitoring systems. Additionally, the cost benefit analysis[1] has demonstrated a significant need for health monitoring in Autonomic Logistics (AL). It is clearly understood and widely known that the diagnostic and control systems are critical components of autonomic health monitoring systems. Success in health monitoring systems hinges upon the prognosis available for the current state of the system. Knowledge of the diagnosis and prognosis of any engineering system enables a better management of resources and time and allows better control of the mission risks, ensured reliability and AL support as described by Hess et al.[2,3] In essence a robust and integrated prognostic health management (PHM) system is essential and critical for AL.

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Assured success in all aspects of critical DoD missions is dominated by high performance sensors. There is a family of sensors which operate with improved and reliable performance and sensitivities if cooled to very low (cryogenic) temperatures (for example various IR sensors), or only operate at these low temperatures (for example those incorporating the effects available due to superconductivity). A mechanical refrigeration system (cryocooler) is required to cool the sensor package to cryogenic operating temperatures and to maintain the sensor package temperature within a specified range during the mission, and safely return the sensor package to ambient conditions at the completion of the mission.[4,5]

The general health of the cryocooler component/subsystem or system is essentially provided in the form of certain diagnostic parameters measured by the sensors at system and component levels. However, the value of these parameters is greatly enhanced if the parameters can be translated to the root cause level and pinpoint the exact location/part or the system and quantify its remaining useful life, probability of failure, and urgency of the situation in order to assure a safe and reliable mission. Additionally, accounting for uncertainties in the variables and degradation mechanisms that govern the performance and reliability (such as fabrication, material, load, operation, environment, component and/or system interface, human factors, etc.) of the component and system is essential to quantify the RRUL. Reliability-based algorithms to predict the RRUL are a key output of the prognostic health monitoring system. Ideas and concepts that elucidate the use of observed parameters of the operating cryocooler to trace back the cause of the degraded performance, impending or actual failure of the component and system, are critical to system modeling.

This paper describes the development of predictive prognostic models that utilize expert knowledge and historical data including past performance, degradation modes, and uncertainties in the involved variables to predict RRUL. Cryocooler Prognostic Health Management System, (CPHMS) software is capable of assessing the cryocooler "health" to determine the level of performance degradation and/or the potential for near term failure. CPHMS utilizes data accumulated during actual missions, past performance test data of similar cryocoolers and a highly adaptable ground based "test cart" that can be employed to assess the cryocooler condition at an even higher level. This system is tailored to take advantage of the fundamentally unique operating characteristics of the free-piston Stirling cryocooler. The evaluation system allows identification of questionable cryocooler operating characteristics in a logical physics-based manner based on a detailed understanding of the various failure modes / performance degradation mechanisms present in the cryocooler. This will allow an informed decision to be made on whether to replace the cryocooler module or perform the mission with the current or repaired hardware.

CRYOCOOLER SYSTEM AND FAILURE MECHANISMS

The current CPHMS system is based upon a generic infrastructure using the Object-Oriented Language architecture and is applicable to a multiplicity of cooler configurations. However, the existing CPHMS development focused on small, single-stage, free piston linear drive devices, employing a tactical Stirling cycle. As a result, the degradation / failure mechanisms to be evaluated and implemented in the CPHMS are unique to the Stirling coolers. Evaluation and quantification of several degradation mechanisms related to wearing, contamination, intermittent seal contact and debris generation, or long-term linear drive system component changes are generally critical in assessing the health of the cooler and limited life requirements. It should be noted here that the cooler operation is affected by the cold tip temperature, insulation package, linear drive motor, the controller performance and operating frequency and therefore are essential to the health management system.

Figure 1 is a diagram of a typical hardware Stirling cryocooler system employed in the CPHMS development effort. The unit provides in excess of 1 W of cooling at a temperature of 75 K in an ambient environment and utilizes a Stirling cycle. An opposed piston linear drive compressor provides input power to the refrigeration cycle. The expander assembly is coupled to the compressor via a transfer tube. The expander itself contains the moving displacer / regenerator assembly, mechanical springs, and the cold finger assembly. The sensor is mounted to the cold tip of the latter and surrounded by a highly efficient insulation package. As noted in Figure 1, the electrical power to drive the linear motors is provided by a power conditioner / controller which receive their power

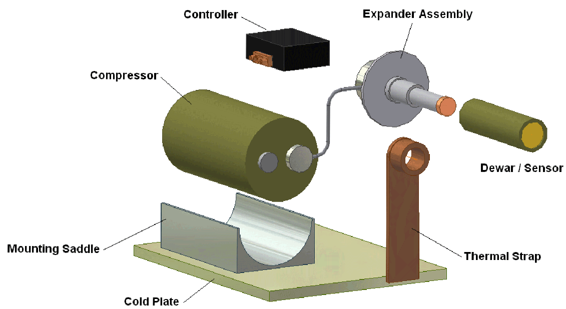

Figure 1. Reference cryocooler configuration and key components.

from the system platform. The entire cooler system is mounted to a cold plate that acts as the final heat sink. In the application under investigation this cold plate is maintained within a specific range of temperatures. A number of thermal paths exist between this cold plate and the linear compressor and expander assembly all of which are critical to overall cooler operation. Each individual cryocooler system is part of a larger cryocooler "array" (6 or more coolers) which operates in an integrated manner. From the viewpoint of the CPHMS the controller is a "black box" which converts the available electric power provided by the platform into useful electrical power for the cooler at a specific frequency and a variable voltage (dependent on cooling capacity requirements and cold head temperature).

Various stages in the life of a cryocooler in the design operating environment and ability of the cooler to meet the required function such as cool down time are key to determine the health and/or failure of the cooler. CPHMS adopts the inability of the integrated system not to function to its full capacity as a failure of the cryocooler. Note that the cooler may still function but fails to deliver the required functional performance. A key issue in the implementation of a successful CPHMS is to be able to use the limited number of available operating parameters and data to not only determine the health but also point the root cause of the failure and assess remaining useful life.

General failure and/or degradation mechanism in Stirling class of coolers are listed in Table 1. These mechanisms are broken down into two classes – the first is the "external" degradation / failure which is noted by the end user while the second class is that which in many cases are internal to the cooler itself and may have contributed to the previously noted external degradation. This latter group represents the thrust of the diagnostic and prognostic effort.

From this information the key "end user" complaint is related to some form of degradation resulting in the cooler not meeting the stringent cool down time requirements. From the "internal" identified degradation / failure mechanisms it is evident that excess drag / wear on the seals for both the displacer and piston are a significant common area. It is important to note that the impact of this mechanism on overall cooler functionality is dramatically different for the displacer and piston assemblies. For example, piston drag effects are of little importance until the electrical input power limits of the power supply are approached – the linear motor simply uses more power to overcome the drag and cooling capacity is not affected. On the displacer assembly both the dynamics and thermodynamics of the cooling cycle are impacted potentially leading to a rapid degradation of overall cooler performance.

CPHMS DESCRIPTION

The implemented CPHMS concept is based on its capacity of assessing the cryocooler "health" to determine the level of performance degradation and/or the potential for near term failure. It utilizes the data accumulated during actual missions, past performance test data of other similar cryocoolers and an adaptable ground based test cart which can carry out specific diagnostic tests at a level of sophistication / detail which is not possible during actual mission. Through the use of specialized test sequences, data collection via readily installed (and removed) test sensors, existing

Table 1. Reported / identified degradation and failure modes

Failure mechanism	**Comments**
External	
Failure to cool to temperature in specified time	
Cooler does not function	Generally after considerable unnoticed degradation or failure related to electrical side or mechanical spring
Internal	
Displacer seal / bearing drag	
Piston seal / bearing drag	
Poor or loss of entire cooler system thermal connection to platform heat sink	System level problem
Thermal coupling (or loss of) to cold plate	Displacer / expander assembly
Regenerator contamination	
Loss of Dewar insulation effect	
Excessive seal wear	Generally related to piston
Excessive seal leakage	Generally related to displacer assembly
Failed mechanical spring	Piston assembly
Partial loss of gas pressure	
Controller "errors"	
Thermal coupling (or loss of) to cold plate	Compressor
Electrical shorts	
Magnet degradation	Excess temperature exposure (>110 C) while operating required
Failed mechanical spring	Displacer

cryocooler system sensor / controller parameters, and the use of cryocooler simulation models, the described integrated CPHMS package allows all of the critical cryocooler parameters to be identified. Also, the evaluation system allows identification of questionable cryocooler operating characteristics in a logical physics-based manner based on a detailed understanding of the various failure modes / performance degradation mechanisms present in the cryocooler.

Additionally, the concepts of modeling uncertainties and performing the probabilistic and reliability analyses are incorporated in the CPHMS to quantify the reliable remaining useful life (RRUL) of the cryocooler components and/or system in real time and use on aircraft systems. Important steps and technical approach used related to Cryocooler Prognostic Health Management System (CPHMS) model and tool development are: (i) Identify reference/primary cryocooler configurations, their components, subsystems and system, (ii) Define and identify critical failure modes and controlling variables and related uncertainties at component and system level, (iii) Implement life prediction and degradation models for components, subsystems and the system, (iv) Implement physics-based prognostic models defining the operating characteristics and cryocooler health/conditions, (v) Apply reliability-based tools to compute RRUL, (vi) Develop a database of the available test data and verify/validate the CPHMS, (vii) Integrate the above in a user friendly object-oriented CPHMS software tool. A general flowchart of the CPHMS design involving key modules of CPHMS is given in Figure 2 and screen snap shot of the software shown in Figure 3.

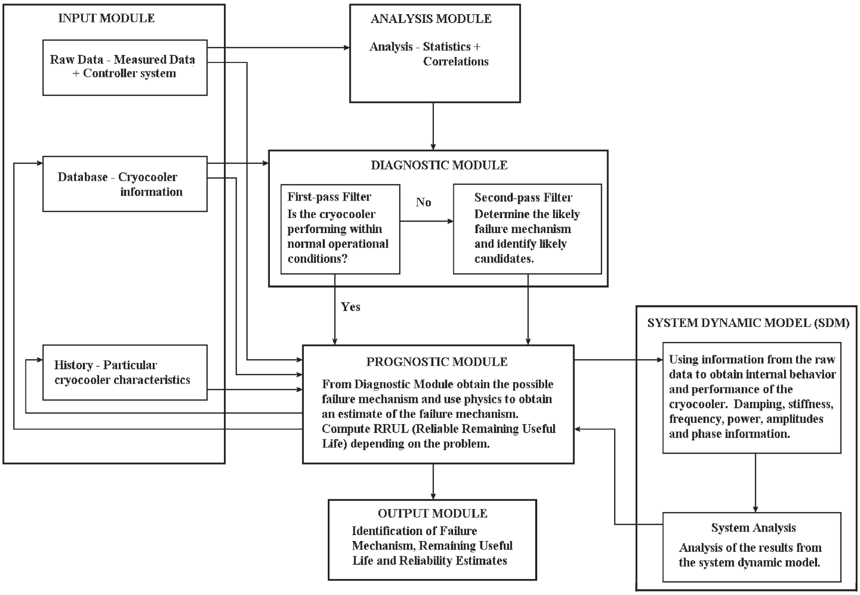

Figure 2. Flowchart of the CPHMS design.

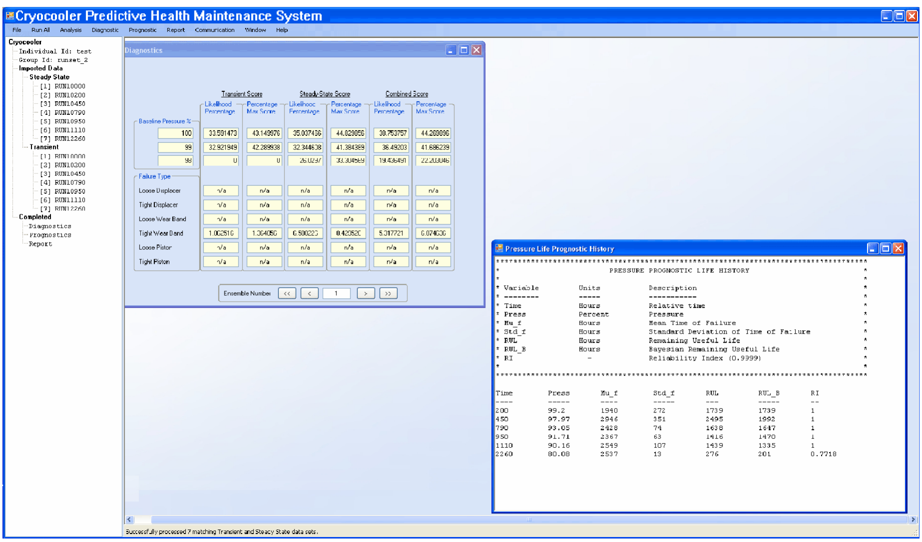

Figure 3. Cryocooler Prognostic Health Management System (CPHMS)

Note that the CPHMS development is complex with varied demand. However, its development is generic, object-oriented and modular in order to make it flexible and powerful enough to accommodate easy expansion, modification, installation and execution in order to cater to the need of adding other existing and new classes of cryocoolers as well software and communication protocols.

EXPERIMENTAL DATA ANALYSIS

The project entailed developing and implementing physics-based models for a particular class of cryocooler in the CPHMS. In order to verify and recognize failure mechanisms, actual data was needed to provide insight into the interior behavior of the cryocooler. A series of experiments was designed and tested on actual hardware. The data, from healthy and "degraded" coolers was expected to be in the form of power and temperature time series, which would be used to give a baseline for the cryocoolers to provide the least invasive techniques required to capture interior behavior. The time series were adapted to get temperature or power time series, first passage problems associated with time, cross correlations between temperature and power, motor variability, fluctuation about the cool down temperature or power frequency, etc. The initial data set for a healthy cooler was prepared to provide a baseline nominal performance.

The baseline nominal performance is required to establish and judge the results from the various failure mechanisms. The data could be from one or many cryocoolers alone, but could also include all external systems, power variation, sensor control and data. Using the combination of results, the models were analyzed and modified in real time to see how large a data set was needed to get relevant information needed to do a diagnosis/prognosis of a cryocooler.

The methodology uses direct measurements of externals from the control system. Each data set was set up to be non-intrusive meaning no modifications were made to the cryocooler. It would provide a reasonable data stream, which could be expected in a realistic cryocooler system without doing a major redesign of the cryocooler (measuring internal pressure differences, piston and displacer motions, and internal flow measurements). This data stream would provide enough information to assess health of the cooler.

CPHMS DESCRIPTION

The diagnostic system design does a simple form of filtering to get a weighted estimate of the possible faults or failure modes. The diagnostics were done using a two-step process; the first cut uses a simple one step pass or filter to determine whether or not the cryocooler was operating within "normal" condition or if it needed to go through the further analysis. The second step is a more extensive investigation of the post-processed data from the transient and steady-state operation of the cryocooler.

The first-pass filter uses the results from the steady-state analysis to determine whether operating parameters are outside of normal bounds. The results are general and more consistent for various temperature and load conditions. The baseline or "normal" acting cryocooler has a fixed probability distributional area for the voltage and current, which is used as a filter as shown in Figure 4.

The second-pass filter uses a comparative study of the cryocooler with other failure mechanisms for variety of test parameters to make a diagnosis and provide a direction to the prognostic system.

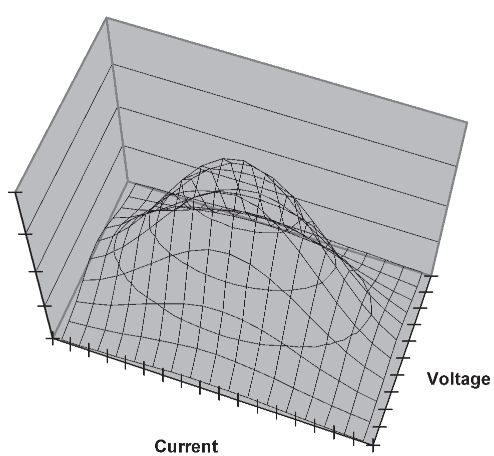

Figure 4. The first-pass filter for the voltage and current distribution

SYSTEM DYNAMIC MODEL (SDM)

Physics-based modeling, one of the salient features of the developed CPHMS, uses several thermodynamic, mechanical and electrical aspects of the modeling techniques. System Dynamic Modeling (SDM) is used to study the internal behavior. The results of SDM simulation together with results of other analysis techniques including the Bayesian are used to perform diagnosis and prognosis to quantify RRUL of the cryocooler. Using steady state analysis of SDM and numerical models, it is possible to obtain the piston and displacer amplitude, velocity and acceleration from the data. In Figure 5, the data from the steady-state operation shows a cycle of the current and voltage waveforms. The flattening of the current wave appears to represent the end of the cycle of the piston or the end of the cycle of the displacer. The voltage and current waves had a spike occurring at the same time section. The spike is characteristic of a slide and drag friction component of simple oscillator.

The displacer and the piston equations have been modeled and an optimization system has been used to get physics-based representation of the two coupled equations. The actual data from the cryocooler was used to get an idea of the behavior of the piston and coupled with the diagnostic results to get behavior of the displacer.

Simplified numerical equations were adapted to represent the current/voltage, piston and displacer models and the relationships between various parameters. Using the parameters of a normally operating cryocooler, the system dynamic model was modified to give relatively accurate behavior for varying environment. The SDM module was used to investigate the internal behavior of the system with data from various degradation/failure mechanisms. The internal behavior of a standard operating cryocooler for variable environmental conditions can be used as a baseline to compare with results from various failure mechanisms. For example, required piston amplitude must be increased to overcome the tight wear band condition (TWB) and the equivalent displacer amplitude increases in the model.

PROGNOSTIC SYSTEM

A general overview of the developments in prognostic systems is presented by Kothamasu,[6] which gives a general overview of the current paradigms and practices. Heng[7] presents some of the challenges and developments in machine prognostics and Li[8] looks at the development of condition-based maintenance. These papers give a general flavor for what is currently being done. Developed CPHMS has unique aspect of physics-based modeling and employing the reliability based techniques including the Bayesian to quantify RRUL, a primary objective of the CPHMS. The diagnostic algorithms are used to identify the degrading mechanism and related component/cryocooler area.

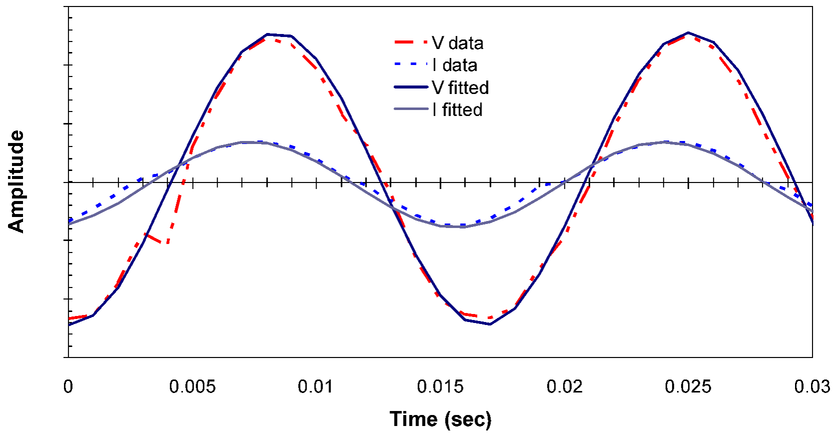

Figure 5. The plot shows a time series of the cryocooler from the steady-state operation.

The prognostic system uses information from the analytical, diagnostic, and SDM modules of the package to make a forecast of remaining useful life. The forecasting of the remaining useful life is dependent on how the cryocooler is stressed, external temperature and loading conditions. A series of algorithms were developed for estimating remaining useful life of the cryocooler for various conditions, pressure loss, failure mechanisms, normal operations, etc. These algorithms must take into consideration, the loading, time between runs and duration of the ensemble in the forecasting.

The loss of pressure in the cryocooler has a distinct set of characteristics and can be “easily” recognized. The main goal of the pressure prognostics is to estimate how long the cryocooler can last with a small leak. The algorithm was designed to monitor how the internal pressure is changing over time and determine how long it would take to reach a point where the cryocooler will have an operational/functional failure. The prognostic algorithm uses the characteristics of the developed parameters to determine the remaining useful life of the cryocooler. The characteristics of the prognostic parameter are shown in Figure 6 and Figure 7 for a 100% charge and a cryocooler with a 90% charge, respectively.

Figure 8 show plots of how the distributions shift with decreasing pressure charge. These results vary depending on external temperatures. The behavior of the prognostic parameter shows how the mean and standard deviation change due to the loss of pressure which provides data for estimating RRUL. An analytical solution was obtained to model the behavior of cooler with the losing of internal pressure and provide a technique for forecasting remaining useful life.

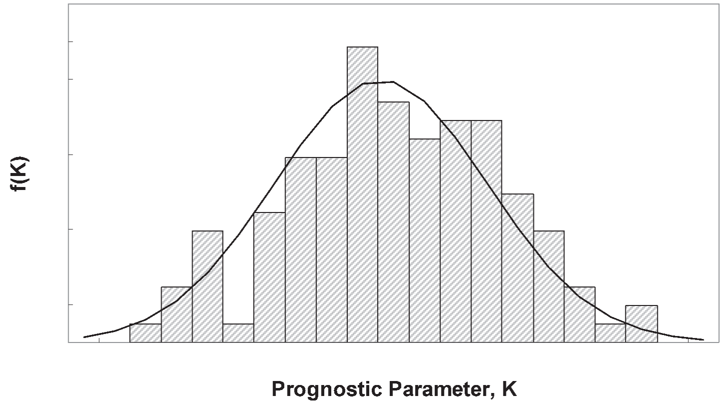

Figure 6. Distribution of the prognostic parameter for 100% charge at room temperature

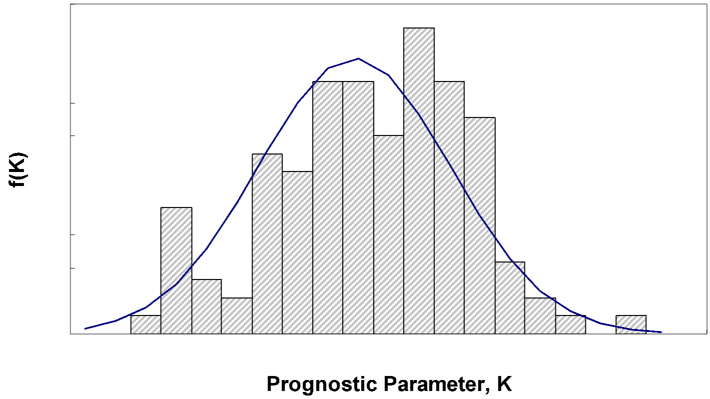

Figure 7. Distribution of the prognostic parameter for 90% charge at room temperature.

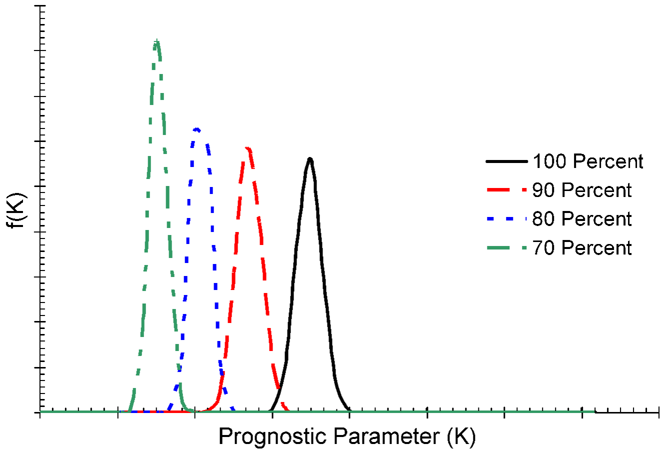

Figure 8. The prognostic parameter, K, distributions at room temperature.

In the testing of the prognostic algorithm for pressure loss type degradation, a series of ensembles, which were both simulated and actual data ensembles, were used for the testing of CPHMS. The failure of cryocooler in the verification test was designed to have a constant pressure loss over 2500 hrs. time frame. The program diagnoses the pressure loss as 97%, 93%, 92%, 90%, and 80% as compared to the actual test data being 98%, 95%, 93%, 90%, and 80% respectively. The algorithm used an analytical formulation to estimate the failure time and calculate the remaining useful life.

In Figure 9, the remaining useful life of the cryocooler versus time along with the pressure charge of the period is shown. The individual results are shown for each ensemble and a Bayesian technique was used to get an estimated remaining useful life. The cryocooler could still function: however, the definition of failure is not being able to cool-down in the required time.

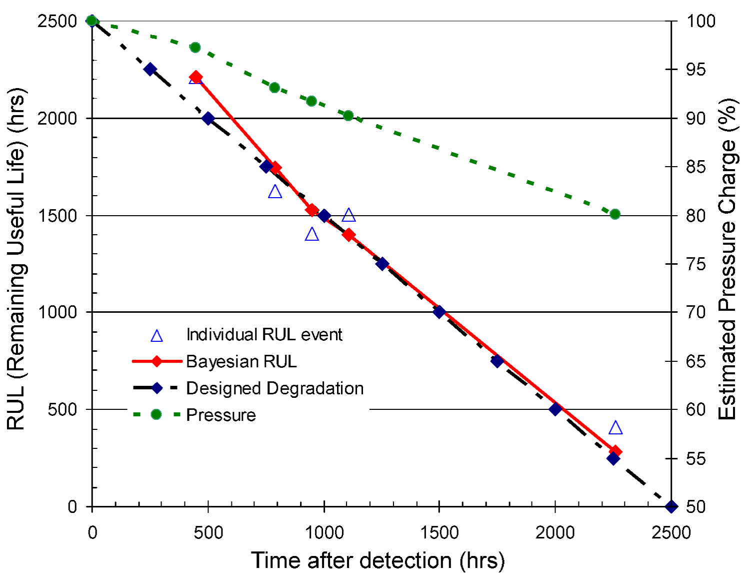

Figure 9. Variation of CPHMS-estimated Bayesian degradation versus the design degradation for pressure loss condition

Figure 10 shows the decay of a cryocooler for tight wear band (TWB) degradation. The first part of the plot shows the design degradation due to TWB with a variable operational time. The orange overlay is the actual degradation at a given time. The second part of the graph shows the remaining useful life of the cooler. The red line is the design degradation, the blue line represents the modified remaining useful life after the extreme events are removed and the black line represents a Bayesian estimation of the remaining useful life. The simulation results were very reasonable.

CONCLUSIONS

A cryocooler prognostic health management system (CPHMS) that is based on the algorithms governing the physics of the cooler behavior and verified with the test data has been developed to estimate the reliable remaining useful life (RRUL) for Stirling class of coolers. CPHMS uses non-invasive means to measure performance of cryocooler with limited data availability and evaluates a variety of failure mechanisms based on a combination of "physics of failure" assessments as well as the results of cryocooler test data of a "healthy" and "degraded" cryocoolers. Used in conjunction with simple models of the fundamental dynamic behavior of linear drive free-piston systems the presence and type of potential degradation mechanisms are identified. CPHMS is generic in nature and the object oriented language has been used in the development in order to enable its easy implementation on different hardware and software platforms and communication protocols. The development is generic in nature and allows other class of coolers to be included easily. Additionally, the CPHMS is capable of handling multiple failure mechanism and uses actual operation data to update the predictions and reliability. Current CPHMS is focused on "tactical" class of cryocoolers; however, the basic approach is easily adaptable to other cryocooler types as well as more complex integrated systems.

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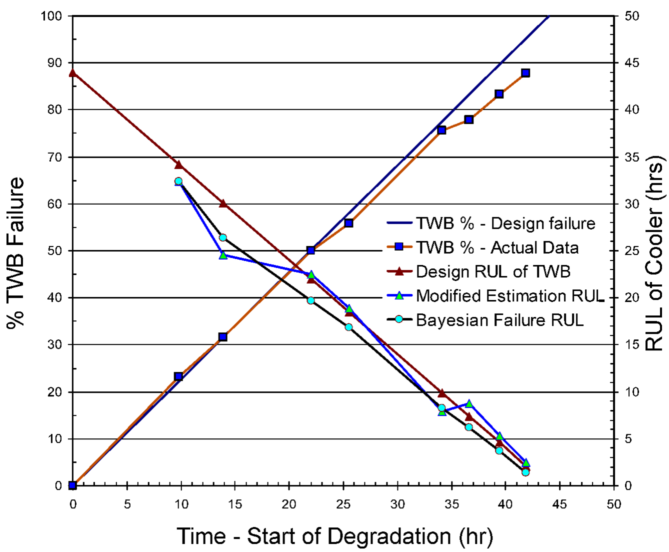

Figure 10. The estimation of simulation of TWB degradation comparing computer code and design degradation.

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