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Superseding AIR5909

Prognostic Metrics for Engine Health Management Systems

RATIONALE

This Aerospace Information Report (AIR) has been superseded by the document AIR7999, "Diagnostic and Prognostic Metrics for Aerospace Propulsion Health Management Systems." AIR7999 consolidates and expands upon the contents of this document (AIR5909) plus AIR4985, "A Methodology for Quantifying the Performance of an Engine Monitoring System." As such, AIR7999 provides a single comprehensive document on diagnostic and prognostic metrics for aerospace propulsion health management systems making the contents of AIR5909 and AIR4985 redundant and unnecessary. This document consolidation strategy was agreed to by the SAE E-32 Aerospace Propulsion Systems Health Management Committee as part of the Committee's Master Plan.

CANCELLATION NOTICE

This Technical Report has been declared "CANCELLED" as of November 2021 and has been superseded by AIR7999. By this action, this document will remain listed in the respective index, if applicable. Cancelled Technical Reports are available from SAE.

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FOREWORD

Engine Health Management (EHM) prognostic technologies are becoming more common and are being tied directly to maintaining engine reliability and performance. The implementation of these prognostic technologies is in turn supporting the more automated and integrated logistics concepts that are being fielded for many commercial and defense systems. This document provides an overview and introduction to the metrics that can be applied for assessing the capability of prognostic technologies for gas turbine engines. This will include a discussion of the required definitions, necessary data sources and a comprehensive set of metrics to assess the performance and effectiveness of prognostic methods.

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1. SCOPE

This SAE Aerospace Information Report (AIR) presents metrics for assessing the performance of prognostic algorithms applied for Engine Health Management (EHM) functions. The emphasis is entirely on prognostics and as such is intended to provide an extension and complement to such documents as AIR5871, which offers information and guidance on general prognostic approaches relevant to gas turbines, and AIR4985 which offers general metrics for evaluating diagnostic systems and their impact on engine health management activities.

1.1 Purpose

The purpose of this AIR is to present metrics that can be applied to assess the performance of prognostic methods. Various metrics are presented and discussed. Additionally, the application of select metrics is illustrated through a given example.

2. REFERENCES

These references contain useful information that may have been used in this report or may be beneficial in understanding the subject matter and its application.

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a finding of Equivalent Level of Safety or a specific exemption has been obtained from the governing regulatory authority.

2.1.1 SAE Publications

Available from SAE World Headquarters, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org

AIR4985 A Methodology for Quantifying the Performance of an Engine Monitoring System

AIR5871 Prognostics for Gas Turbine Engines

ARP5783 Health and Usage Monitoring Metrics Monitoring the Monitor

2.2 External Publications

Byington, C., Roemer, M., and Watson, M., "Prognostic Enhancements to Diagnostic Systems (PEDS) Applied to Shipboard Power Generation Systems," Proceedings of the ASME/IGTI Turbo Expo 2004-Power for Land, Sea, and Air, June 14–17, 2004, Austria, Paper Number: GT2004-54135.

Engel, S. J., Gilmartin, B. J., Bongort, K., and Hess, A, "Prognostics, The Real Issues Involved with Predicting Life Remaining," IEEE 0-7803-5846-5/00, 2000.

Kacprzyński, G. J., Hess, A. J., and Begin, M., "Metrics and Development Tools for Prognostic Algorithms," 2004 IEEE Aerospace Conference, March 6-13, 2004, Big Sky, MT.

Koutsoukos, X., Biswas, G., Mylaraswamy, D. A., Hadden, G. D., Mack, D., and Hamilton, D., "Benchmarking the Vehicle Integrated Prognostic Reasoner," 2010 Annual Conference of the Prognostics and Health Management Society, October 10-16, 2010, Portland, OR.

Frederick, D. K., DeCastro, J. A., and Litt, J. S., "User's Guide for the Commercial Modular Aero-Propulsion System Simulation (C-MAPSS)," NASA/TM-2007-215026, October 1, 2007.

Patrick, R., Smith, M. J., Byington, C. S., Vachtsevanos, G. J., Tom, K., and Ly, C., "Integrated Software Platform for Fleet Data Analysis, Enhanced Diagnostics, and Safe Transition to Prognostics for Helicopter Component CBM," Annual Conference of the Prognostics and Health Management Society (PHM10), October 13-16th, 2010, Portland, OR.

Roemer, M. J., Dzakowic, J., Orsage, R. F., Byington, C. S., and Vachtsevanos, G., "Validation and Verification of Prognostic and Health Management Technologies," 2005 IEEE Aerospace Conference, March 5-12, 2005, Big Sky, MT.

Roemer, M., Byington, C., Kacprzynski, G., and Vachtsevanos, G., "An Overview of Selected Prognostic Technologies with Application to Engine Health Management," GT2006-90677, Proceedings of ASME Turbo Expo 2006: Power for Land, Sea and Air, Barcelona, Spain, May 8-11, 2006.

Roemer, M. J. and Byington, C.S., "Prognostics and Health Management Software for Gas Turbine Engine Bearings," ASME Turbo Expo 2007: Power for Land, Sea, and Air, Paper #GT2007-27984, Montreal, Canada, May 14-17, 2007.

Saxena, A., Celaya, J., Balaban, E., Goebel, K., Saha, B., Saha, S., and Schwabacher, M., "Metrics for Evaluating Performance of Prognostic Techniques," IEEE International Conference on Prognostics and Health Management, October 6-9, 2008, Denver, CO.

Saxena, A., Celaya, J., Balaban, E., Saha, B., Saha, S., and Goebel, K., "Evaluating Algorithm Performance Metrics Tailored for Prognostics," 2009 IEEE Aerospace Conference, March 7-14, 2009, Big Sky, MT.

Saxena, A., Celaya, J., Balaban, E., Saha, B., Saha, S., and Goebel, K., "On Applying the Prognostic Performance Metrics," Annual Conference of the Prognostics and Health Management Society (PHM09), September 27 - October 1, 2009, San Diego, CA.

Saxena, A., Celaya, J., Balaban, E., Saha, B., Saha, S., and Goebel, K., "Evaluating Prognostics Performance for Algorithms Incorporating Uncertainty Estimates," Aerospace Conference, 2010 IEEE, March 6-13 2010, Big Sky, MT.

Saxena, A., Celaya, J., Saha, B., Saha, S., and Goebel, K., "Metrics for Offline Evaluation of Prognostic Performance," International Journal of Prognostics and Health Management, vol. 1, no. 1, p. 20, 2010.

Sen-Gupta, J., Trinquier, C., Medjaher, K., and Zerhouni, N., "Continuous Validation of the PHM Function in Aircraft Industry," 2015 Prognostics and System Health Management Conference, October 21-23, 2015, Beijing, China.

Uckun, S., Goebel, K., and Lucas, P. J. F., "Standardizing Research Methods for Prognostics," IEEE International Conference on Prognostics and Health Management, October 6-9, 2008, Denver, CO.

Wheeler, K. R., Kurtoglu, T., and Poll, S. D., "A Survey of Health Management User Objectives in Aerospace Systems Related to Diagnostic and Prognostic Metrics," ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, August 30–September 2, 2009, San Diego, CA.

2.3 Definitions/Acronyms/Abbreviations

Acronyms

ARMA	Auto-Regressive Moving Average
B	Average Bias
C-MAPSS	Commercial Modular Aero-Propulsion System Simulation
CRA	Cumulative Relative Accuracy
EHM	Engine Health Management
EGT	Exhaust Gas Temperature
EoL	End-of-Life

EoLP	Predicted End-of-Life
H	Horizon
LLP	Life Limited Part
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
PH	Prognostic Horizon
RA	Relative Accuracy
RUL	Remaining Useful Life
S	Sample Standard Deviation
UUT	Unit Under Test

Definitions

t	time
t_F	time index when fault of interest initiates
t_D	time index when fault is detected by diagnostic system
t_P	time index when prognostic prediction begins
t_{EoL}	actual time index when UUT reaches its end-of-life or failure threshold
t_{EoLP}	predicted time index when UUT will reach its end-of-life or failure threshold
i	index representing time index t_i
$i_{\alpha\beta}$	the first time index when predictions satisfy the β -criterion for a given α -bounds
k	index representing the k^{th} UUT
ℓ	number of time indices where predictions are made between t_P and t_{EoLP}
L	number of UUTs
p	set of all time indices when predictions are made
$r_{actual}^k(i)$	actual RUL at time i for the k^{th} UUT
$r_{predicted}^k(i)$	predicted RUL at time i for the k^{th} UUT
w	weight factor
$\Delta^k(i)$	error, or difference between calculated and actual end-of-life for the k^{th} UUT at time t_i
ϕ^k	prediction of variable of interest for the k^{th} UUT

$\phi^k(i j)$	prediction of variable of interest for the k^{th} UUT at time t_i given data up through the time t_j
$\Phi^k(i)$	trajectory of future predictions of ϕ^k defined as $\{\phi^k(i i), \phi^k(i+1 i), \dots, \phi^k(EoLP i)\}$
α	accuracy bounds on prediction
α^+	maximum allowable positive error
α^-	maximum allowable negative error
β	minimum desired probability threshold
λ	time window modifier such that $t_\lambda = t_p + \lambda(t_{EoL} - t_p)$
$\phi(x)$	non-parameterized probability distribution for any variable x
$\pi[RUL_{predicted}] _{\alpha^-}^{\alpha^+}$	probability mass of the prediction residing within the defined α -bounds

3. PROGNOSTIC METRICS FOR EHM SYSTEMS

Engine health management (EHM) systems play a critical role in assisting operators in managing the reliability, availability, and affordability of their gas turbine engine assets, which may also provide an intrinsic enhancement to safety. The functionality provided by an EHM system includes the capability to evaluate the current health of the system (diagnostics) as well as the emerging approach of predicting or forecasting the future health of the system (prognostics).

The emphasis and need for effective prognostic methods continues to grow. The desire for condition-based maintenance, optimal scheduling and performance of maintenance, and fleet management are all technology pulls. Operators are facing prognostic technology design choices, and with these choices, they require an effective means to compare the relative performance and benefits of different prognostic methods. The purpose of this document is to set forth a series of metrics that can be applied to quantify the performance of EHM prognostic algorithms.

3.1 Engine Prognostics

A prognostic entails the prediction in time of the health state of a system relative to some threshold. Prognostics is the ability to predict the future condition of a component and/or system of components. For the purposes of gas turbine engine prognostics, this definition is often further described in terms of life (usage) consumption of a component or the rate at which a faulted component continues to degrade. Generally speaking, prognostics can be delineated into two different categories: Usage-based prognostics and Health-based prognostics. These are defined as follows [Patrick, et al, 2010]:

Usage-based Prognostics: Combines usage monitoring (load/stress tracking) with a wear or life model to estimate the rate at which a component degrades, accumulates damage or “consumes” its design life. The prognosis estimates the remaining design life at any given time. It can track wear or degradation in parts and can also offer support for replacement logistics. It can reduce risk of conventional time-based or cycle-based approaches when usage is intense. Usage-based prognostics does not take into account unanticipated faults, and is most applicable for components that degrade as intended by design. It does require an estimate of future system usage to provide its prognosis.

Health-based Prognostics: Combines health monitoring (fault assessment via diagnostics) with a fault/damage progression model to estimate the rate at which a faulted component continues to degrade. It is capable of tracking a degraded condition (once a fault or anomaly is detected) and providing early warnings for components in need of maintenance due to unanticipated faults or the presence of damage. Health-based prognostics works only as a follow up to the detection of a fault or anomaly (i.e., requires a positive diagnosis of a fault or anomaly), which immediately implies that the prognosis is operating over a damaged component that is at risk of failing. It is important that the initial diagnosis of a fault is performed correctly, as a false alarm or misclassification can lead to nonsensical results in the ensuing prognostic predictions.

Prognostics involves calculation of the Remaining Useful Life (RUL) of a Life Limited Part (LLP), component, or subsystem. Naturally, a prediction of any kind is not an exact science. The intent of a statement of RUL is to provide a time horizon that maximizes time in use without compromising functionality, i.e., removal before or at predicted end-of-life can be accomplished to prevent failure from occurring with minimal risk of the loss of functionality. There is always a degree of uncertainty which arises from variations inherent in manufacturing processes, material batches, installation variances, usage history, and uncertainties in future usage conditions (environmental and operational), etc. Therefore, accounting for uncertainties in life predictions and also when assessing prediction performance is of paramount importance. All prognostic methods include some form of a forecast horizon, which may or may not associate a confidence, or certainty, in the forecast. Metrics described in this AIR present some such metrics that assess performance of both type of prediction methods mentioned above.

To introduce some preliminary definitions regarding prognostics consider Figure 1. In the context of condition-based prognostics shown here is a time history of the actual (solid line) and predicted (dashed line) remaining useful life (RUL) of a Unit Under Test (UUT) for the health-based prognostics (Figure 1a) and usage-based prognostics (Figure 1b) categories introduced above. The RUL versus time plot forms the foundation of the prognostic metrics presented in this document. Consider a situation where n different engines are being monitored from a fleet. In order to characterize performance of our monitoring and prognostics methods we would use metrics for fleet performance. Whereas, if the interest is in predicting life and assessing prediction performance of a specific, say k^{th} engine, the situation would be reflected as shown in this figure. Here, the time index is denoted by i , and information is shown for the k^{th} UUT or an engine in our case. In condition-based prognostics, predictions are updated on a regular basis to take into account actual engine condition as it evolves through usage. Therefore, several predictions are made at different times and the points along the dashed line, $r_{predicted}^k(i)$, represent the predicted RUL at time i for the k^{th} UUT. However, at the end of its lifespan the UUT will have a deterministic failure time. This failure time is also referred to as ground truth and is never known *a priori* in real practice. However, for prediction performance assessment purposes, predictions are compared with this ground truth information. Correspondingly, individual points along the straight solid line, $r_{actual}^k(i)$, represent the actual RUL at time i for the k^{th} UUT. For health-based prognostics (Figure 1a), the process begins with the initiation of a fault at time t_F , followed by detection of the fault by a diagnostic system at time t_D . This is followed by the prognostic prediction of remaining useful life initiating at time t_P , after a suitable amount of data has been accrued to initiate the prognostic process. The actual and predicted end of remaining useful life are denoted as t_{EoL} and t_{EoLP} , respectively. In most cases, the UUT will be replaced prior to reaching its estimated end-of-life. Not all health-based prognostic processes strictly adhere to this sequence of events. In some instances, the time of fault detection and the time of prognostic prediction initiation could be the same. The usage-based prognostics process is shown in Figure 1b. Here, the prediction of remaining useful life begins when the component or system is first introduced into service at time, t_0 . An example would be an engine life limited part such as a disk. In such cases, there is no fault initiation or fault detection event to trigger the process. Remaining useful life calculation begins immediately upon entry into service. For both health-based and usage-based prognostics, the prognostic method is tasked with updating the RUL calculation at each time step. While RUL calculations vary by application and approach, they inherently involve the calculation and forecasting of a variable of interest representing system health. Examples include a crack propagation length, a part effective cycle count, or remaining exhaust gas temperature margin. A predicted future trajectory of this parameter through the point of system failure, t_{EoL} , enables the RUL to be estimated. This is illustrated in Figure 2. Here, the predicted variable of interest is denoted as ϕ^k , and $\phi^k(i|j)$ denotes a point prediction of this variable at time t_i given data up through the time t_j . A trajectory of future predictions of this parameter from time t_i onward is given as $\Phi^k(i) = \{\phi^k(i|i), \phi^k(i+1|i), \dots, \phi^k(EoLP|i)\}$. This trajectory is updated each time step as additional data becomes available. The difference between predicted end-of-life time, t_{EoLP} , and current time, t_i , defines predicted RUL: $r_{predicted}^k(i) = t_{EoLP} - t_i$.

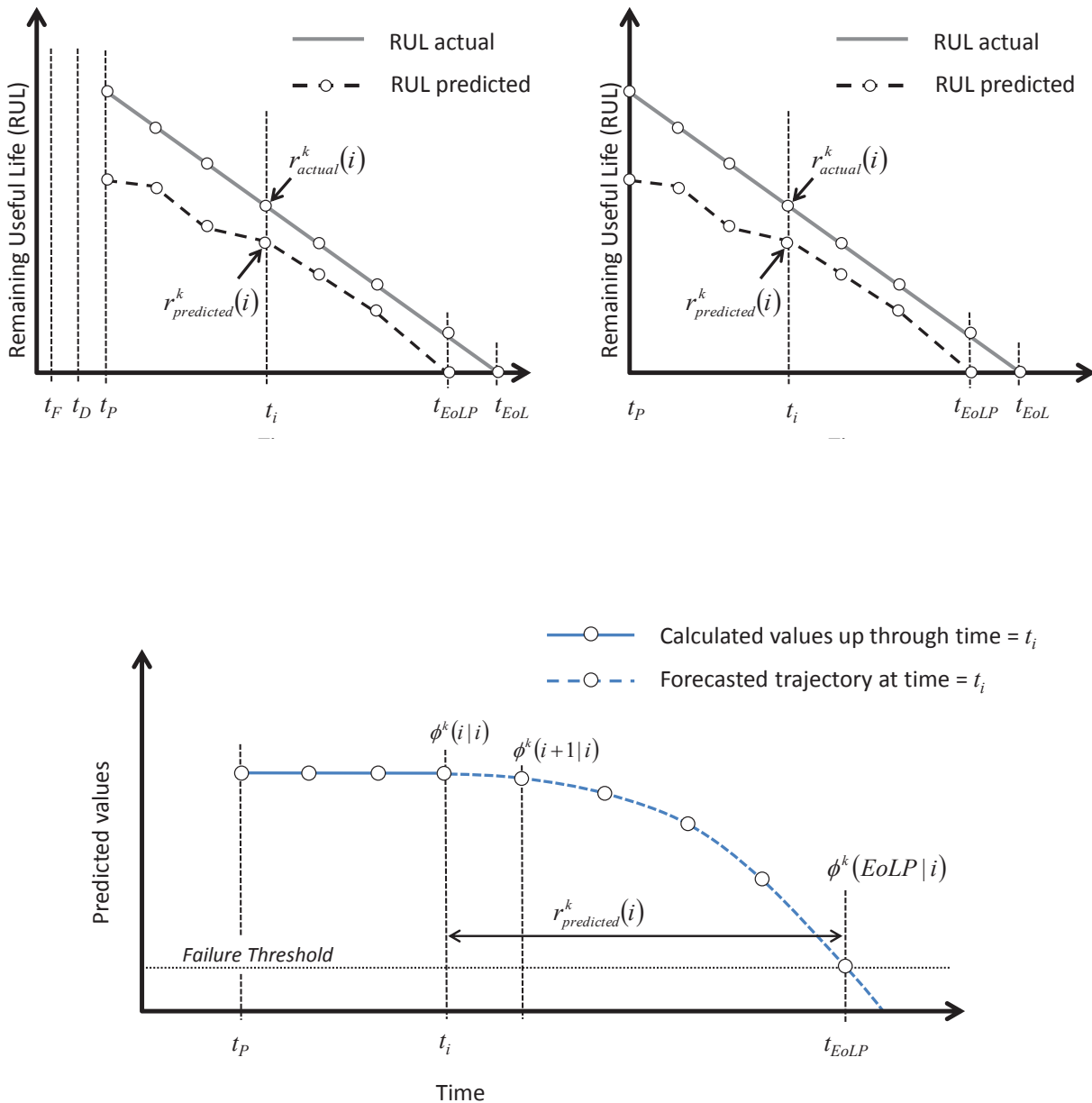


Figure 2 - Illustration of trajectory prediction and RUL calculation

Another key aspect in prognostics is that of uncertainty in predictions. Any post-prognostic decision, whether safety or cost related, must be taken in light of uncertainty in predictions. Uncertainty in prognostics arises from inaccuracies in modeling, measurement noise, errors in state estimation, and uncertainties in future loading and operational conditions. None of these factors can be completely eliminated and therefore, prognostics algorithms now include adaption routines to characterize, represent, and propagate these uncertainties into the future estimates of system states. Consequently, prognostic performance metrics have become more sophisticated in dealing with prognostic uncertainty beyond initial concepts of precision in RUL probability distribution. For a complete discussion of prognostics for gas turbine engines readers are referred to AIR5871.