



AEROSPACE INFORMATION REPORT

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(R) Prognostics for Aerospace Propulsion Systems

RATIONALE

This Aerospace Information Report (AIR) was developed to provide insights and examples of how prognostic algorithms can be used in support of monitoring and maintaining aerospace propulsion systems, with an initial focus on gas turbine engines and their subsystems. This revision includes updates reflecting the aerospace industry's latest thoughts on when prognostic algorithms are useful and how they can be classified. This revision also includes expanded examples to reflect common methods which have been used in the field.

FOREWORD

Prognostic technologies that are capable of predicting component failures or performance degradation rates are expected to improve safety and availability, reduce life cycle costs, and optimize the timing of scheduled maintenance intervals. For many engine components and subsystems, prognostic approaches are currently being developed that utilize state-of-the-art modeling and analysis technologies. This document introduces and provides examples of leading prognostic modeling approaches that integrate state-of-the-art analytical and empirical models with component testing and inspection results. Specific examples related to engine performance degradation and remaining useful life for a helicopter gearbox are described, along with a representative range of different technical approaches. The process of prognostic model calibration and verification is also discussed.

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1. SCOPE

1.1 Purpose

This document applies to prognostics of aerospace propulsion systems. Its purpose is to define the meaning of prognostics in this context, explain their potential and limitations, and to provide guidelines for potential approaches for use in existing condition monitoring environments. This document also includes some examples. The current revision does not provide specific guidance on validation and verification, nor does it address implementation aspects such as computational capability or certification.

1.2 Field of Application

This document applies to the field of Prognostics and Health Management (PHM) and seeks to meet the increasing interest in prognostics for aerospace propulsion systems. Specifically, the document tries to provide a timely guideline for applying prognostic technologies to enhance the capability of current monitoring and diagnostic systems. Some examples are provided that are intended to illustrate different approaches and methodologies.

2. REFERENCES

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 specific exemption has been obtained.

2.1 Applicable Documents

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR7999 Diagnostic and Prognostic Metrics for Engine Health Management Systems

2.1.2 Other Publications

Daigle, M., Saha, B., and Goebel, K., "A Comparison of Filter-based Approaches for Model-based Prognostics," Proceedings of IEEE Aerospace Conference, Big Sky, MT, Mar. 2012.

Gelb, A. (Ed.), "Applied Optimal Estimation," MIT Press, Cambridge, MA, 1974.

Glaessgen, E., and Stargel, D., "The digital twin paradigm for future NASA and US Air Force vehicles," 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA. 2012.

Lytle, J. K., "The Numerical Propulsion System Simulation: A Multidisciplinary Design System for Aerospace Vehicles," NASA/TM-1999-209194, 14th International Symposium on Air-Breathing Engines (ISABE), <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19990062672.pdf>, Florence, Italy, 5-10 Sept. 1999.

Orchard, M., and Vahtsevanos, G., "Aparticle-filtering approach for on-line fault diagnosis and failure prognosis," Transactions of the Institute of Measurement and Control 31, 3/4 (2009) pp. 221–246.

Patrick, R., Orchard, M., Zhang, B., Koelemay, M., Kacprzynski, G., Ferri, A. and Vachtsevanos, G., "An integrated approach to helicopter planetary gear fault diagnosis and failure prognosis," 42nd Annual Systems Readiness Technology Conference, AUTOTESTCON 2007, Baltimore, MD, Sept. 2007.

Rozas, H., Jaramillo, F., Perez, A., Jimenez, D., Orchard, M., and Medjaher, K., "A method for the reduction of the computational cost associated with the implementation of particle-filter-based failure prognostic algorithms," *Mechanical Systems and Signal Processing* 135 (Jan. 2020) 106421.

Simon, D. L., "Propulsion Diagnostic Method Evaluation Strategy (ProDiMES) User's Guide," NASA/TM—2010-215840, Jan. 2010.

2.2 Acronyms

APU	Auxiliary Power Unit
ARMA	Autoregressive Moving Average
EFH	Engine Flight Hours
EGT	Exhaust Gas Temperature
EOL	End of Life
KF	Kalman Filter
MRO	Maintenance, Repair, and Overhaul
MTBF	Mean Time Between Failure
MTBI	Mean Time Between Inspections
NASA	National Aeronautics and Space Administration
OEM	Original Equipment Manufacturer
PDF	Probability Density Function
PHM	Prognostics and Health Management
ProDiMES	Propulsion Diagnostic Method Evaluation Strategy
RUL	Remaining Useful Life
TLD	Time-Limited Dispatch

3. GENERAL

3.1 What is Prognostics?

In general, prognostics is an engineering discipline focused on making a statement about a future event that would affect system functionality, with at least some understanding of the timeframe in which it will happen. It should be recognized that in practice, there are several different interpretations of what is included in prognostics. They range from mean time to failure estimates (which are based on statistics of large populations of the same type of components) to interrogating the condition of a particular component using sensors and estimating the remaining life using algorithms customized for the condition at hand. The basis for these predictions are quite different and dictate how the results of prediction need to be interpreted.

3.2 Potential Benefits of Prognostics

- Improved Operational Availability
- Reduced Life Cycle Costs
- Optimized Maintenance/Inspection Intervals

- Provides confidence in completing a mission since no known issues are forecasted
- Inventory and Asset Management

3.3 When Prognostics is Valuable

When applying prognostics it is critical to ensure that the value of the prognostic outweighs the cost of developing, fielding, and maintaining the data collection and analysis system. There are many instances where it is possible to predict future behavior, but the utility of that prediction is not of practical value.

Figure 1 illustrates three key timeliness considerations that help determine the value of prognostics for any application. In order to fully understand the implications of Figure 1, it is important to distinguish between the terms “fault” and “failure.” Failure, or functional failure, refers to the end point on the right of Figure 1, and is characterized by the inability of a system, piece of equipment, component or subassembly to fulfill its design purpose. Functional failure is the most severe degree of malfunction or degradation. A fault, or incipient fault, is just the presence of symptoms indicating a condition which may be indicative of an impending failure.

1. Minimum early warning to plan and carry out Maintenance, Repair, and Overhaul (MRO): Different systems and respective maintenance processes impose constraints on time horizons required for planning and execution. Assessing the amount of time needed to take action without disrupting operations requires an understanding of the logistics support system. This includes the maintenance action which will be required to address the incipient fault, and having a sense of how long it will take to arrange a convenient opportunity with the parts/equipment necessary to perform the maintenance action. This defines minimum requirements on early warning that a prognostic system should yield such that it allows maintenance action to be performed during pre-existing maintenance windows. See the “Minimum window for MRO” in Figure 1.
2. Prognostic Horizon of the prognostic algorithm: One characteristic of a valuable prognostic algorithm is that the amount of time with which a failure can be predicted (with sufficient accuracy) is greater than the amount of time needed to take action without disrupting operations as explained in (1) above. As illustrated in Figure 1, this length of time is known as the prognostic horizon. Prognostic horizon is generally a function of signal-to-noise ratio in monitoring data and efficacy of the chosen prognostic algorithm/method. Point P occurs at or after point D (fault detected) in Figure 1. There may be a delay between points D and P to diagnose the fault and achieve the desired level of certainty in the prognostic output.
3. Fault propagation rate and detectability: Fault modes propagate at different time scales, e.g., Li-ion battery thermal runaway can propagate in a matter of seconds, whereas battery capacity degradation may take on the order of weeks. Assessing the prognostic horizon requires an understanding of the level of difficulty in detecting the incipient fault given the robustness of the sensing capability and knowing how quickly the fault typically progresses to functional failure. Gradual failure modes with precursors which can be detected well in advance such that (1) and (2) described above are satisfied are generally good targets for prognostics. It is important to remember that no matter how good your detection capability is, if a fault progresses too quickly, the potential actions available may be limited.

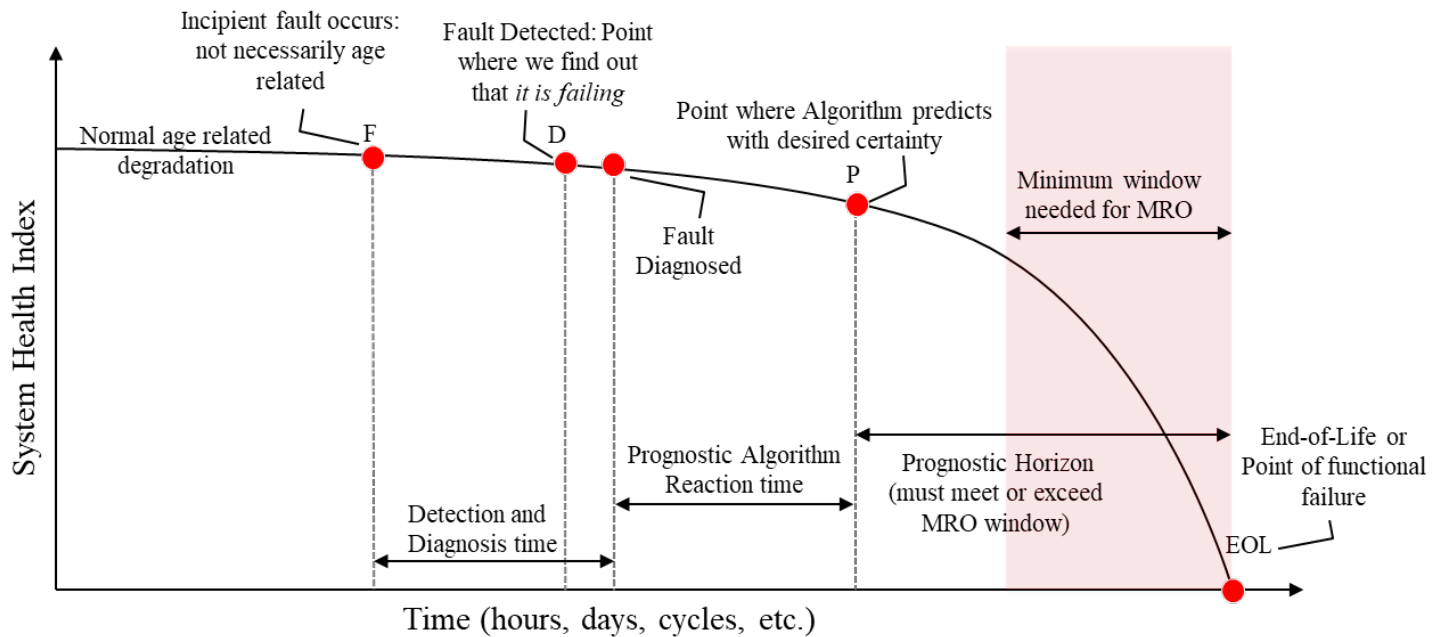


Figure 1 - Key events in prognostic assessment

Another characteristic of a valuable prognostic algorithm is that the robustness of the approach used to predict time remaining is commensurate with the criticality of the failure. In cases where the consequence of the failure is a minor disruption, a less robust approach with limited accuracy may be acceptable. However, in cases where the failure can result in grounding an aircraft or affecting the flight crew, it is only appropriate to apply a prognostic approach when it is very accurate and repeatable.

In applications which utilize Time Limited Dispatch (TLD), it is important that any prognostic algorithms complement the TLD coverage and not duplicate coverage. For example, if short time dispatch is already allowed for a given failure mode, a prognostic algorithm for that failure mode will be of minimal value, since operations can continue even when the component fails. It is best to focus prognostic development activities on faults which can directly result in a no dispatch condition.

3.4 Considerations for Prognostic Requirements

To develop the requirements for a prognostic system, the developer/end-user might first consider the following:

- The level of condition degradation beyond which operation is undesirable.
- Operation-based input on how much lead time is needed to respond without affecting operations. This should be considered in terms of the likely range of deterioration rates and the amount of time it will take from detection to functional failure (See 3.3 discussion on timeliness considerations).
- Understanding of uncertainties inherent in the prognostic process and their impact on maintenance decisions, and quantification of uncertainty measures.
- The prognostics performance metrics which will be used as success criteria. In general, it is advised that the fault detection statistics and diagnostics accuracy be specified separately from prognostic accuracy. Refer to AIR7999 for further discussion on metrics.

4. PROGNOSTIC APPROACHES

To better understand and communicate the characteristics of various prognostic strategies, it is helpful to classify each approach based on the characteristics which apply to it. One way to do this is to specify the output type, category, model type, and method for each prognostic approach.