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Superseded by ARP5120

Engine Monitoring System Reliability and Validity

RATIONALE

This SAE Aerospace Information Report (AIR) has been superseded by a completely new document, Aerospace Recommended Practice ARP5120, which provides guidance on how to develop and implement an integrated end-to-end health management system for gas turbine engine applications. ARP5120 consolidates SAE Aerospace Information Reports AIR1873, AIR4061B, AIR4175A, and AIR5120 into one document per the direction of the SAE E-32 committee.

CANCELLATION NOTICE

This Technical Report has been declared "CANCELLED" as of November 2016 and has been superseded by ARP5120. 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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1. SCOPE

1.1 Purpose

For Engine Monitoring Systems to meet their potential for improved safety and reduced operation and support costs, significant attention must be focused on their reliability and validity throughout the life cycle. This AIR will provide program managers, designers, developers and customers a concise reference of the activities, approaches and considerations for the development and verification of a highly reliable engine monitoring system.

When applying the guidelines of this AIR it should be noted that engine monitoring systems physically or functionally integrated with the engine control system and/or performing functions that affect engine safety or are used to effect continued operation or return to service decisions shall be subject to the Type Investigation of the product in which they'll be incorporated and have to show compliance with the applicable airworthiness requirements as defined by the responsible Aviation Authority. This is not limited to but includes the application of software levels consistent with the criticality of the performed functions. For instance, low cycle fatigue (LCF) cycle counters for Engine Critical Parts would be included in the Type Investigation but most trend monitors and devices providing information for maintenance would not.

1.2 Introduction

An Engine Monitoring System (EMS) adds value by providing real time or near real time information on the functional and physical condition of gas turbine engines. This information is used to alert operators to conditions that could impact safe operation, schedule inspections and repairs to improve functional performance, forecast spares requirements, and manage warranties.

The elements that comprise an EMS are discussed in ARP1587. When discussing the reliability and validity of an EMS, the entire system needs to be considered, (i.e., design philosophy, software, hardware, sensors, operating procedures, training, service introduction and field support). The reliability and validity of the EMS is only as strong as its weakest sub-element.

Prior to the advent of EMS, engine operational information was obtained from flight crew and maintenance personnel observations gathered during operation or inspection. While there is no known quantification by a regulatory authority of the reliability and validity of these manually based approaches, they have evolved into the procedures and regulations that are currently considered the reliability baseline. Today, most EMS automate and enhance some or all of the manual processes to increase equipment safety and reduce operating cost.

Many early attempts to introduce EMS have lacked total success for a number of reasons. One of the major factors was a general lack of reliability. This reliability shortfall has come, in part, from the inherent unreliability of the system hardware elements. More importantly, however, reduced reliability was often due to the unreliability of the information provided by the system. History is replete with examples of false alarms, ranging from false chip detector lights to more sophisticated systems producing many false fault codes per flight. The inability of early EMS to provide reliable information has caused many to be extremely cautious in deciding how or when to implement a system.

2. REFERENCES

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 specific exemption has been obtained.

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 724-776-4970 (outside USA), www.sae.org.

ARP1587 Aircraft Gas Turbine Engine Monitoring System Guide

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

2.2 Definition of Terms

Detailed definitions of some of the terms below are given in AIR4985.

BIT: Built in Test

EIS: Entry into Service

FALSE ALARM: The indication by the EMS that a problem condition exists when no problem is present.

MISSED DETECTION: The non-indication by the EMS of a problem condition that it was designed to detect.

CORRECT DETECT: The correct indication by the EMS that a problem exists.

EMS RELIABILITY: $\frac{[\text{Total Indications} - \text{False Alarms} - \text{Missed Detections}]}{\text{Total Indications}} * 100$

FIR: $\frac{[\text{No. of faults isolated}]}{\text{No. of faults indicated}} * 100$

ENGINE MONITORING SYSTEM (EMS): An EMS is defined as the complete system involved in the monitoring and indication of engine health. Included are the component level and subsystem level health status indications. Such indications are obtained through the use of sensor input, data collection, data processing, data analysis, and the human decision process. A complete system approach consists of an integrated set of hardware, software and logistical process. It can be manual, computer aided or fully automated.

COULD NOT DUPLICATE (CND): The inability to duplicate a problem detected by an EMS during subsequent testing. CNDs can be classified in two ways and can be difficult to separate:

1. A problem does not exist (False Alarm)
2. A problem does exist but is not detectable during the current test, i.e., no fault found, NFF. The principle cause of CNDs is the absence of a failure mode symptom during test conditions. In such cases, maintenance and operations personnel should take the appropriate action based on their experience. The suspected cause can be addressed by replacing components or the system can be returned to service with no maintenance action to see if the indicated fault returns.

LIFE CYCLE COST (LCC): LCC refers to the cost of the engine system of which the EMS is an integrated part. One of the main drivers behind most EMS is a reduction in engine system LCC. Included in the LCC is the cost of the EMS system and all additional hardware and software. The reduction in the LCC achieved as a result of the benefits derived from the EMS should be greater than the added cost of the EMS. From a general perspective the following gives the LCC Return on Investment (ROI).

Life Cycle Cost = Cost of EMS + Cost of Engine System + Cost of Operation Over Life
ROI = $\frac{[\text{Benefit of EMS} (\$) / \text{Cost of EMS}]}{1} * 100$

Where Benefit of an EMS can be defined as

Cost of Operation without EMS - Cost of Operation with EMS = EMS Cost Benefit

When an EMS is applied to a system already in service, consideration must be included for the years of remaining service. Depending upon the business aspects, it may be necessary to conduct a more in-depth financial analysis of the system to include a break-even analysis or spending profile projections as required by the business managers. The details of such analysis activity will generally be specific to the company but will generally follow the above indicated concept.

3. GENERAL CONSIDERATIONS

3.1 Overview

One of the fundamental reasons for incorporating an EMS is to improve the Life Cycle Cost (LCC) of the monitored system through operational and maintenance benefits. In most cases, the EMS supplier will specify a Return on Investment (ROI) for the system. The ROI analysis has to be developed in conjunction with the engine Manufacturer or Design Authority, who has detailed knowledge of the engine's operation, performance and failure modes. Unreliability of the EMS will adversely affect the ROI and could make the EMS a cost burden. The technology that is available for integration into an EMS is a primary driver of both ROI and reliability. There is a direct trade off between risk and reliability. Any technology that is not fully matured may result in additional cost and risk to the program if it fails to perform. This applies to all the items associated with the EMS such as analysis techniques, sensors, hardware and software.

It is preferable to start planning for an EMS early in the requirements development phase during the period where the customer, aircraft manufacturer and engine manufacturer have the flexibility to optimize content while maximizing reliability and ROI. Input from the customer's operational functions as well as the maintenance personnel who will use the system daily will provide an early understanding of the level of functionality required of the EMS and how it will be used. It is important at this stage to produce a risk assessment of technologies and to prepare maturation plans for those considered which offer high benefits as well as high risk. Consideration of these points up front should allow the EMS to be integrated into the total system architecture as outlined in Section 4.

A requirement may exist to retrofit an EMS, possibly to address a particular problem with the engine and its maintenance. Delayed introduction of an EMS to in-service engines will be more costly and may result in a less than desirable EMS capability but still yield a substantial return on investment and positively impact maintenance, logistics, safety, and operations. Retrofit of an EMS is by far the most complicated method of improving an existing system. Experience shows that for in service aircraft the cost of additional hardware, such as wiring and transducers to provide data for the EMS, may outweigh the benefits. In this case the best approach is to retrofit during a scheduled upgrade of the engine or airframe, particularly if wiring and sensors are to be added. The reliability requirements and considerations are the same as for the ideal case. However, the added complexity of integration into service, operational equipment and practices has to be considered in the risk assessment.

Human factors are an important element of EMS reliability. Since humans must ultimately interface with the system the risk of inducing human error exists and the associated impact on reliability. Section 4.5 details Human Factors and methods to mitigate their effects.

The entry into service and use of an EMS should be planned during the design phase. The EMS is likely to have an impact on the maintenance and operating procedures of the engine. The planning will include consideration of training and operation and maintenance procedures for the EMS itself and also for the engine. This is covered in 4.6.

Testing is a fundamental requirement to demonstrate EMS reliability and validity. Recommended test procedures to improve EMS reliability and validity are presented in Section 5 of this AIR together with their roles in terms of improving reliability and validity.

The functionality and use of the EMS should be integrated into the appropriate operational and maintenance practices for the air vehicle to improve the perceived and actual reliability of the EMS. Considerations for introduction of the EMS into service are addressed in Section 6.

The entry into service and support and maturation of an EMS will affect the reliability and validity of the system. If use of the functions is not fully integrated into the in-service environment, the overall reliability and validity of the system will be compromised. Issues related to integration into service and support and maturation are addressed in Sections 6 and 7.

3.2 General Validity and Reliability Requirements

EMS reliability needs to be evaluated at the system functional level in contrast to evaluating the inherent reliability of each hardware and software element. An EMS cannot be more reliable than its most unreliable hardware or software element. This is still true if the system includes redundancy to accommodate element malfunction.

EMS reliability is a function of 'false alarms' and 'missed detections'. False Alarms lead to time and money being spent verifying or trouble shooting a problem that does not exist. Although specific requirements are system and operator dependent, the target EMS false alarm rate on some of today's applications is no more than 2% of all the messages/alarms generated as a result of the faults monitored by the EMS. Provisions should be made during the requirements phase to consider the impact on the ROI and optimize accordingly.

EMS 'missed detections' result in equipment problems that go undetected. Missed detections generally have less impact than 'false alarms' since most equipment is designed to degrade slowly and equipment problems are eventually detected by the EMS or by the operating or maintenance crews. EMS 'missed detections' only become significant if the problem causes severe secondary damage or catastrophic equipment failure. Failure modes associated with severe or catastrophic failure usually make up only a small percentage of the equipment failure rate. Typically, these failure modes are well scrutinized during the EMS system design to avoid missed detections. This scrutiny is driven by the criticality of these failure modes and usually results in the EMS functions for these failure modes becoming part of the flight critical crew alerting system.

False Alarms have a far greater potential of negative consequences than Missed Detections. Therefore, as a guiding principle, EMS designers should focus considerable effort on avoiding false alarms even to the extent that missed detections are tolerated. As will be discussed later in this document, the EMS designer (in conjunction with the OEM) must make many decisions during the system and hardware/software design phases that directly impact reliability.

4. DESIGN AND DEVELOPMENT ACTIVITIES

4.1 System Specification

The operator/customer/OEM, in conjunction with the EMS designer, will normally create a system specification that defines the requirements of the overall system. It is recommended that EMS reliability and validity requirements be specified as part of the system specification. Specifications should include acceptable false alarm and missed detection rates, detection and diagnostic capabilities, and key implementation requirements (i.e., hardware, software and system integration). In each case, it is important that the system specification clearly identifies the requirements so that the system configuration and approach are selected to ensure that the requirements are met. The integration of the EMS with other existing or planned aircraft or engine systems such as the engine control, aircraft busses, and logistics management systems should also be clearly identified. Dependency on other systems has to be considered in the design and testing of the EMS and will have an effect on the reliability and validity of the system.

The system specification should also identify how the EMS information and data will be integrated into and used in the engine's operational and maintenance procedures. The reliability of the EMS in meeting the target improvement in LCC will be affected by how the data and information is used. Particular attention should be paid to interface architecture since different suppliers or organizations are often responsible for portions of the system to be integrated. All these activities have to be carried out with the engine Design Authority (DA/OEM).

Each specific application will carry slightly different reliability and validity goals determined by safety, cost and ROI considerations. These reliability and validity goals need to be established in the early stages of the design process and can then be used by the EMS designer to determine the implementation, hardware and software architectures, and testing levels.

The Acceptance Test Specification should be developed once the system specification has been prepared. This should include testing to address the reliability and validity requirements.

4.2 Hardware

EMS hardware reliability depends on the reliability of the EMS components and architecture. The correct hardware architecture of the EMS may improve functional reliability and validity of the detection capability and diagnostics. The separation of the functional requirements of the EMS for monitoring and acquisition should be considered during the definition of the EMS architecture.

The following key points should be specifically addressed:

- High reliability for the on-board components of the EMS, used for alerting the crew during flight.
- Reduced reliability may be acceptable for ground based elements of the EMS since the reaction to the information presented is not as critical in the post-process mode as it is for the real time on board mode. There is potential for additional ground based verification of the result. This practice is not recommended, however it may be used as a cost-effective solution.
- Reliability of data transfer from the airborne to ground based system is influenced by hardware, media, handling, related procedures, etc.
- The communication between the EMS and other related aircraft, engine and logistics systems.
- EMS needs to be designed sufficiently robust so that failure of any one of the interfaces will not adversely affect the communication and performance of the remaining interfaces and the EMS should continue operation in the degraded mode.
- Allow sufficient tolerance bands between components to include variance that could occur as a result of changing suppliers during the production phase.
- Match timing requirements between digital signal processors.

Although the redundancy of the sensors, communication lines and processing electronics will positively influence functional reliability of the EMS it is not general practice to have redundant components of the EMS or redundant processing electronics. Redundancy of some of the measured parameters may be implemented in the Engine Electronic Control or Full Authority Digital Electronic Control, EMS can benefit from this data.

The environment in which the components operate influences reliability of the EMS. The environmental requirements are usually stated in the specification and include such parameters as:

- Mechanical load - vibration, shock - single, multiple, linear acceleration, acoustic noise.
- Temperature - high, low operating/maximum short time/survival temperature, rate of change of temperature.
- Atmosphere - atmospheric pressure, rate of atmospheric pressure change, humidity, condensed humidity.
- Resistance to salt spray, sand and dust, fungus, working liquids, water, internal icing.
- Electromagnetic - atmospheric electricity, high intensity radiated fields (HIRF), lightning strike - single and multiple, multiple burst.
- Power Supply - normal, abnormal power supply conditions.

During the design phase environmental requirements defined in the specification are analyzed and the equipment is either designed to meet the specification, or measures are taken to reduce load on the components of the system:

- The mechanical loads are usually reduced by installation in an area with lower vibration levels or by means of shock absorbers.
- Operating temperature of the units can be reduced by cooling - forced cooling by air, fuel or natural cooling by convection.
- Operating temperature of the units can be increased by heating or by better heat dissipation inside the unit.
- Electromagnetic protection is usually provided by the whole EMS, including sensors, cable assemblies, and electronic unit(s). Special attention is paid in this case to proper shielding and grounding. The electronic unit(s) itself should also survive certain levels of interference induced by lightning, electromagnetic interference (EMI) or high intensity radiated fields (HIRF). For very demanding military environments fibre optic transmission of signals and communication may be required.

In general EMS should recognize normal and “abnormal” operating conditions. In case of abnormal operating condition such as intermittent power supply or lightning strike, the EMS should not output false information. Depending on the requirements, it should either keep silent or continue to output the last measured valid data set for a short time, as defined in the specification. After the normal conditions resume, the EMS should continue operating in normal mode.

The general requirement for the EMS is that elements should be replaceable without additional adjustments or degradation of measurement accuracy. The hardware design should provide long term stability.

4.2.1 Electronics

The following design practices increase functional reliability of the EMS electronics:

- Shielding, grounding and impedance matching.
- Separation of power and sensitive data lines.
- Operating below the power rating of the components.
- Burn in, aging processes during assembly and testing of the units.
- EMI protection on the input, output and power supply interfaces of the EMS.
- Separation of the “clean” and “dirty” zones within the electronics unit.
- Provision of a ground test (maintenance) connector with buffered signals to allow monitoring of the units operation during development, troubleshooting and other maintenance actions.
- Incorporation of spare computation power of at least 30 to 50% and spare memory of at least 20 to 50% is highly recommended to preclude potential reliability issues related to future growth of the EMS.
- Provisions for on board software or configuration upload to allow continuing upgrade and maturation of the EMS.
- System integration testing prior to and as part of final design verification testing preferably in a phased approach that gradually steps up the level of integration. (i.e., bench test to engine test to aircraft test) (refer to Section 5).