PREDICTIVE MAINTENANCE IN AVIONICS

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OVERVIEW

This paper presents a method of degradation assessment for electronic equipments and its integration within the avionics maintenance architecture. The health monitoring function is based on physics of failure approach. At first, we explain the current centralized maintenance concept, and then we present a description of the built in health monitor function integration at board level, and the communication process with the maintenance data centralizer.

1. INTRODUCTION

Today, in the aeronautical field, maintenance represents the most expensive task during the aircraft life cycle. More and more manufacturers in the aeronautical area are involved in many research projects which aim is to elaborate technical solutions and associated technologies allowing to decrease maintenance costs. The main headline of these projects is to increase the aircraft operability by improving the on board maintenance system performances. In this way, this paper focuses on the integrability of a new predictive maintenance function based on prognosis health monitoring. This new function should take place inside the current avionics architecture. The integrated vehicle health management system concept, foreseen for next generation aircrafts, should consider such prognosis requirements. The objective is the assessment of the remaining lifetime of operability-driving components and of the foreseeable serviceability of the aircraft. Indeed, we expect that the embedded prognosis function shall detect the state degradation of all circuit boards and provide an estimation of their life time remaining with a great confidence level. The prognosis function should also be able to interpret an initial set of environmental measures or intrinsic parameters for a final state board assessment. Nevertheless, during the operational phase, the health monitoring should also be useful as much as possible for diagnosis, troubleshooting, and localization purpose. In this paper we will put forward a health monitoring methodology to provide such prognostic information. But at first we will present the principles of avionics centralized maintenance. Then, we will focus on the new methodology allowing the estimation of life consumption monitoring based on the impact of temperature and vibration stresses. Finally we will propose a new architecture merging current diagnosis functions and new prognosis capabilities.

2. CURRENT MAINTENANCE PROCESS

The current maintenance processes for avionics equipments concerns two categories of replaceable units the Line Replaceable Unit (LRU) and Shop Replaceable Unit (SRU):

- The LRU is a component which is designed to be removed and replaced by line maintenance operator on aircraft with time constraints (the intervention should last no more than 20 minutes).

- The SRU is a part of a LRU and is designed to be removed and replaced in the shop

The current maintenance process of avionic systems and their constitutive units is based on BITE results (BITE = Built-In Test Equipment). Each BITE gives the functional status of the LRU in real time during flight. This principle is described in figure 1. All the failures are detected and recorded as well as their contexts (time, other parameters values) during the flight by each subsystem after an adequate filtering.

The subsystem which has detected a failure also sends, according a predefined sequence, the relevant test code to the maintenance data manager. This computer generates a functional warning to the cockpit depending on the failure. Depending on this test code, ground crew is able to identify the faulty part and also the maintenance action to perform.

The maintenance operations can be made through 2 complementary modes: on-board and on-ground.

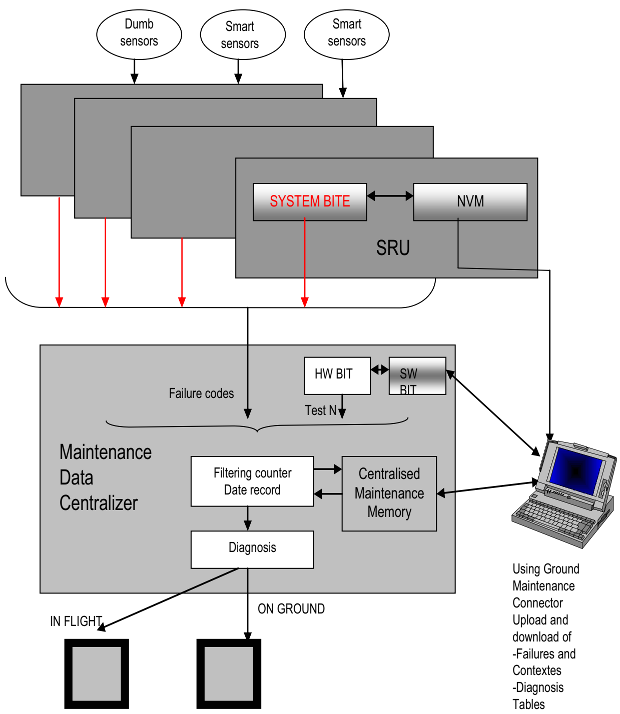


FIG 1. Overview of on board maintenance system with ground tool

- A dedicated on board maintenance mode will gather basic data concerning the failed LRU or modules of the whole system. Primary flight display sensors, radio and navigation sensors data is concentrated in a specific flight systems manager. Vehicle and engines sensors data is concentrated in a specific vehicle data manager. When a failure is detected by a subsystem the context data is recorded in the subsystem and a report is delivered to the maintenance data manager. In operational mode during flight the maintenance data manager delivers an identification of the faulty LRU to the dumb displays, should it be localised with a good level of confidence (this level of confidence is stated according to FMECA analysis which allows to know for each test the concerned LRU's).
- For the ground mode, maintenance ground station can be linked to the system. Thanks to the complementary data recorded during flight, the ground maintenance station performs the best diagnostic [3]. On aircraft, the avionics maintenance manager delivers a failure report that can be shown through cockpit displays, Off aircraft, a specific maintenance computer can be linked to a helicopter connector and allows to access directly to each subsystem through an RS422 link. This computer allows to access to the context data which mainly consists in value of parameters when discrepancy is detected, status of BITE when HW failure is detected and record of status label of sensor when sensor failure occurs. Thanks to these data an enhanced report is delivered on the computer. In ground maintenance mode, the maintenance data manager delivers on request the list of the tests which have detected a failure (localised or not) and the list of LRU which are probably involved. In ground tool mode, every subsystem acts separately and delivers on request, all the recorded events, parameters and data linked to the failures. These data are downloaded and displayed on the ground tool. All the test codes received by maintenance data manager are recorded. Data are therefore used for diagnosis and localisation step.

Further to this description, we can observe that on board maintenance system is very strictly connected to the performances of the BITE. The BITE health assessment provides a binary result which is OK or FAILED. BITE does not allow us to know the life time remaining estimation for equipments. Besides, the following chapter presents a complementary method which is dedicated to the description of a physics-of-failure-based methodology for estimating the damage level. For electronic parts the damage level is expressed by life consumption.

3. MODELING PHASIS: PHYSIC OF FAILURE ASSESSMENT

In the avionics field, the demand in reliability knowledge is growing more and more with complexity of systems. The prediction of failure becomes a field of interest because the aircraft operability key driver is a function of the aircraft status knowledge at a given time. In this chapter a methodology of continuous health monitoring is presented.

3.1 Damage modeling

The damage accumulation is modelled by a linear theory, which is the commonly used i.e. the Palmgren-Miner hypothesis. Failure occurs when the cumulative damage is greater than 1. The cumulative damage is the sum of the elementary damages Di. [7]

$$D1 + D2 + ... + Di = cummulative\ damage$$
$$\geq 1\ in\ case\ of\ \ failure$$

The Palmgren-Miner Hypothesis states that the damage faction at any stress level Si is linearly proportional to the ratio of the number of cycles ni of operation to the total number of cycles Ni that would produce failure at that stress level [4]:

$$\sum_i \frac{ni}{Ni} \geq 1 \quad in\ case\ of\ \ failure$$

Thermomechanical damage assessment of component attaches:

Temperature is a key driver that participates in the physical degradation of components. The consequences of temperature gaps can impact the material properties that are at the origin of the corrosion of connections at component attaches level. Temperature parameter can product corrosion due to application of high temperature, local stress concentrations due to non-uniform temperature, and the destruction of metal structures. The thermal cycles can also be at the origin of material deformation. We can model damages and the impact of the temperature environmental parameter at component level. The arithmetic law that is the kernel function of the health monitoring function and that interprets solicitations in terms of degradations is known as the Coffin-Manson plastic strain fatigue life relationship [6]

$$N_f = \frac{1}{2}\left(\frac{\Delta W}{2\varepsilon_f}\right)^{\frac{1}{c}}$$

Where
Nf = median cycles to component failure (number of cycles to 50% of component population failure)
2εf = fatigue ductility coefficient
c = fatigue ductility exponent
ΔW = maximum cyclic strain energy density, function of solder joint and components material properties.

Vibration damage assessment of component attaches:

Some of the common faults that may be caused by vibration include bent shafts, damaged or misaligned drives, bearings, fretting corrosion, onset of cavitations, worn gears [5]. Vibration and shocks can flex leads and interconnects; change positions of parts in the system, cause acoustical and electrical noise, and perturb the structural [5]. Protective measures against vibration and shock are generally determined by an analysis of the deflections and mechanical stresses produced by these environmental factors. This involves the determination of natural frequencies and evaluation of the mechanical stresses within components and materials produced by the shock and vibration environment.
Fatigue due to vibration constraints can be modelled through Basquin equation. For an accurate estimation of damage, the vibration modes should be taken into account with the degradation implied by each mode. For a given vibration mode, the maximum lead/attach

stress is used in the Basquin equation to determine the cycles to [5]

$$S.Nf = Cstt$$

Where:
Nf = cycles to failure
b = fatigue exponent
S = attach's maximum stress, function of solder joint and components material properties.

For both vibration and temperature solicitations we remark that the number of cycle to failure Nf is strongly linked with the nature of the solder material, the dimensions of the components, and more generally, Nf is a function of the board characteristics, and is also a function of the damage model. Given a set of characteristics of the board, each solicitation profile is associated to a number Nf, according to the principle of energy conservation. So, for one type of cycle, we are able to evaluate an elementary damage induced by ni solicitations:

$$Elementary\ damage = \frac{ni}{Nfi}$$

The board modelling and damage model choice is the first step of the health monitoring process. This process is described in the next chapter.

3.2 Board modeling

Board modelling is the first step of health monitoring function building. The damage modelling is a basis input to perform to perform simulation based failure assessment of printed wiring assemblies. An identical computer reproduction of the card is made by software. To perform this model, a list of data is required. This information could be the component Information like package length and width, number of pins (I/O), the lead and weld style, dimensions and material, the actual power dissipation rate, theta JC and the package material. Information at board level is also required like the number of layers, the layer material and thickness and dimensions. Finally the via/plated through holes are characterized by the drill size, the plating thickness and material are also taken into account. The next assessment is conducted based on a defined set of failure mechanism models that have prescribed input requirements that have extracted from the design and data loading. Failure mechanism models include package to board interconnect failure due to temperature cycling, vibration and shock, plated through hole failure due to temperature cycling, die metallization failure due to corrosion electro migration or dielectric breakdown in under temperature, humidity and bias.
From the software modelling phasis we expect minimum temperature and vibration cycles to component solder and lead failure. CALCE PWA software [8] includes thermal analysis, vibration analysis and failure assessment capabilities. The failure assessment is conducted on a defined printed wiring assembly and defined life cycle loading conditions. Based on the hardware and the loading conditions, individual failure sites are identified and time to failure is estimated.
The output of these phasis is a characterization of the board robustness in front of one given external stress cycle which is represented by the number of cycles until failure, thanks to the failure mechanisms models. This output will be helpful for the estimation of an elementary degradation, function of a given stress. This is precisely this transfer function that has to be the useful information to be loaded into the monitoring software part of the SRU in order to make assessments during operational life cycle.

4. OPERATIONAL PHASIS: LIFE TIME REMAINING ESTIMATION

The modelling phasis provide inputs to the operational phasis. This information is essentially the number of cycles to failure for a PCB depending on the environmental stress profile. Besides, the health monitoring process is a succession of several elementary steps: monitoring critical parameters, simplify raw data, extracting the number of cycles and assessing damages, and thus calculating life time remaining [2]. The description of the health monitoring hereunder is limited to the study of the temperature parameter impact but these capabilities has to be extended to other critical parameters like vibration, electric or chemical failures in another study.

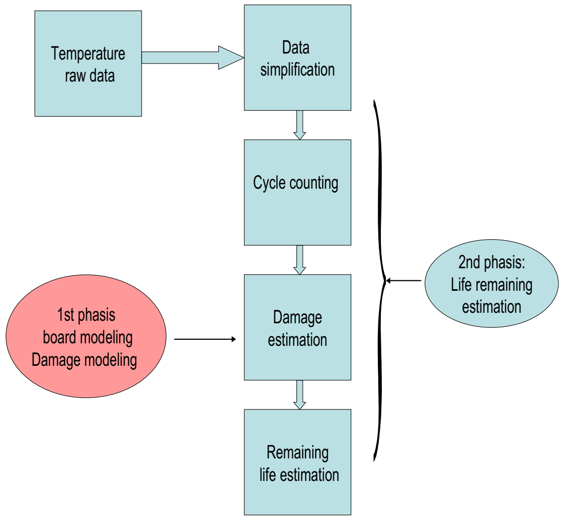


FIG. 2. Overview of Integrated Health Monitoring process

- 1st step data simplification: At first the data is measured and simplified to make this information compatible with the degradation assessment method (broken line) and in order to reduce the mass of information coming from sensors and to reduce the time to make the assessment. The Ordered Overall Range (OOR) method is used to treat the raw data and provides peaks and valleys that could be usable by the next step of the process.

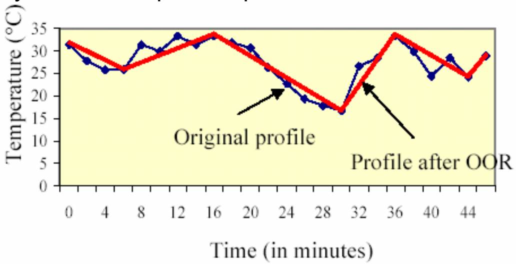


FIG. 3. First step: Data simplification

- 2nd step cycle counting: The useful information is transformed into number of cycles. The cycles are classified and characterized according two values which are the mean temperature of the cycle and the amplitude of the cycle.

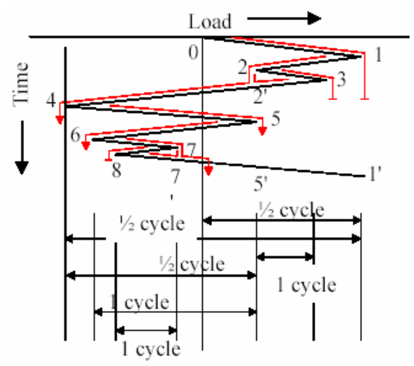
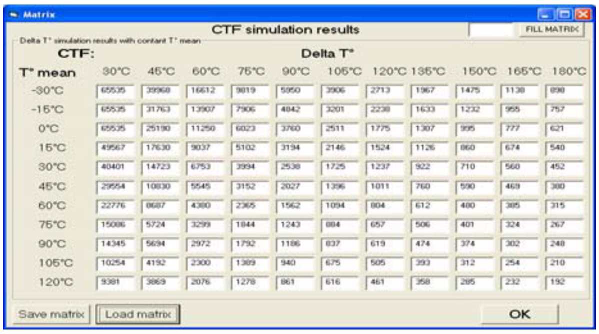


FIG. 4. Second step: cycle counting

- 3rd step: After counting and characterization of each cycle, the corresponding damage assessment is preformed. Previously, in the board modelling phasis and simulation phasis, we provided the number of cycles to failure Nf for each cycle type. The Nf list was previously uploaded into the microprocessor of the monitoring organ into a specific matrix (ΔT, Tmean) [1]. This matrix originally comes from the software modelling and the assessment of the electrical components. Each matrix refers to one specific component. In these operational phasis we enumerate and characterize the cycles coming from the measures. Then we can estimate the associated damage (§3.1). Finally all the elementary damages are summed and the result represents the life time consumption ratio according to the Miner's rule.



Matrix

CTF simulation results

FILL MATRIX

Delta T° simulation results with contant T° mean

CTF: Delta T°

T° mean	30°C	45°C	60°C	75°C	90°C	105°C	120°C	135°C	150°C	165°C	180°C
-30°C	65535	39968	16612	9819	5950	3906	2713	1967	1475	1138	898
-15°C	65535	31763	13907	7906	4842	3201	2238	1633	1232	955	757
0°C	65535	25190	11250	6023	3760	2511	1775	1307	995	777	621
15°C	49567	17630	9037	5102	3194	2146	1524	1126	860	674	540
30°C	40401	14723	6753	3994	2538	1725	1237	922	710	560	452
45°C	29554	10830	5545	3152	2027	1396	1011	760	590	469	380
60°C	22776	8687	4380	2365	1562	1094	804	612	480	385	315
75°C	15086	5724	3299	1844	1243	884	657	506	401	324	267
90°C	14345	5694	2972	1792	1186	837	619	474	374	302	248
105°C	10254	4192	2300	1389	940	675	505	393	312	254	210
120°C	9381	3869	2076	1278	861	616	461	358	285	232	192

Save matrix | Load matrix | OK

FIG. 5. Third step: refer to the matrix containing the number of cycles to failure

5. HEALTH MONITORING INTEGRATION IN MAINTENANCE ARCHITECTURE

The health monitoring (HM) concept objective is to provide life time remaining estimation for an electronic part. One declension of this assumption is: the integrated HM function has to assess the health condition of a board element at a given moment during its operative life. At equipment level it has also to be seen as a mean to anticipate a failure before its occurrence. At aircraft level it can be seen as a mean to make proactive maintenance or a complementary set of compiled information for helping diagnostic purpose. The elementary function is to be implemented at board level, at the same level than BITE concept. Indeed the BITE function provides a result between GO and NOGO, this BITE result is a binary result found into {0,1} whereas the HM function is found into the interval [0,1]

$$BITE : Rawdata\ for\ assessment \mapsto \{0;1\}$$
$$HM : Rawdata\ for\ assessment \mapsto [0;1]$$

Each type of occurrence has the same type of treatment by the Maintenance Data Centralizer (MDC). The principle (fig.7.) is: the degradation observer sends status messages either periodically before failure. Then a new database is created in the MDC which contains a list of SRU with their associated life consumption
Each type of occurrence has the same type of treatment by the Maintenance Data Centralizer (MDC). The principle is: the degradation observers called Built In Health Monitors (BIHM) are integrated at SRU level. They send status messages either periodically before failure. Then a new database is created in the MDC which contains a list of SRU with their associated life consumption.

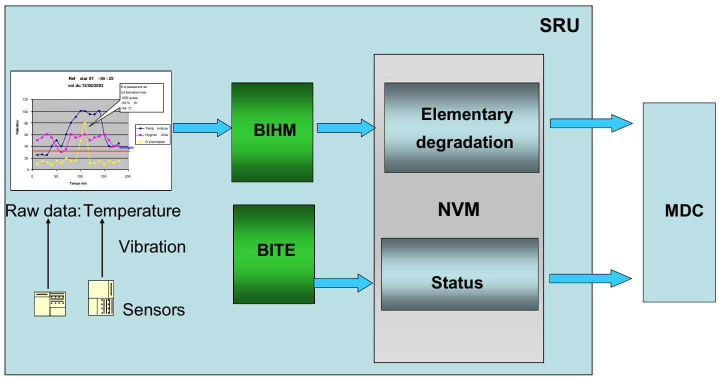


Fig.6. Integration of the Health Monitoring treatment: Built In Health Monitor

The communication between the monitored SRU and the MDC is defined in the previous diagram. A message is sent by the host to the MDC after a significant number of stress cycles impacting the life consumption have occurred.
This message contains an assessment of the life time remaining. Then the MDC database is updated. If a failure occurs, and if the failure is not a fatal failure (which cuts communication between MDC and host) , all the stress info remaining recorded degradation assessments are sent to the MDC in order to help the diagnostic and localization purpose. If a fatal failure occurs, the HM useful data is recorded into the NVM.

On the SRU side, the elementary degradations are then added in order to obtain the health status of the monitored element. The HM algorithms used to assess the remaining life is implemented at SRU level. During operational life, the electronic board is submitted to variable stresses and environmental parameters cycles. The HM function transforms such external constraints into an elementary degradation and feed the MDC with this result.

On the MDC side, all the data is gathered and stocked in order to constitute a database reflecting the health status of all the systems and their constitutive SRUs. The diagram hereunder represents such distribution of SRUs life time remaining. This database is updated after each flight. Besides, when failure occurs some complementary set of information is recorded into the non volatile memory (NVM), the HM results are also recorded into the NVM.

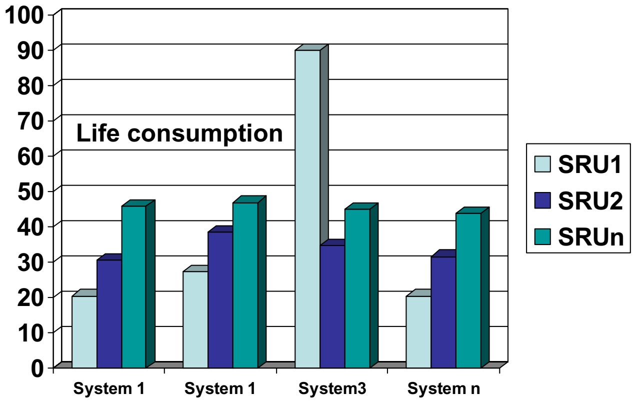


FIG 8. Results of systems status assessment at MDC level

6. PERSPECTIVES

This paper shows the integration of the health monitoring function within the avionic maintenance architecture. The damage assessment process is based on physics of failure models which treat temperature stress and vibration stress separately. However, the interaction resulting from these two main stresses implies complex mechanisms of degradation which the linear law of Miller cannot model. Other parameters linked with electrical, chemical or electromagnetic failures are also to be considered in the failure mechanisms models. The next works can deal with the enrichment of the BIHM by a not linear approach. Then we can experiment the enriched BIHM into the avionic standards thanks to a dedicated prototype. Then will can study the performances of the prototype and compare it with the oldest architecture.

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