Prognostics Health Management and Failure Analysis Modeling techniques for Accelerated Life testing in Electrolytic Capacitors

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Agenda

- Motivation and background
- Approach
- Electrical accelerated aging experiments
- Thermal accelerated aging experiments
- Degradation modeling
- Prognostics method and results
- Discussion
Motivation

- Electronic components have increasingly critical role in on-board, autonomous functions for
  - Vehicle controls, communications, navigation, radar systems
- Future aircraft systems will rely more on electronic components
- Assumption of new functionality increases number of electronics faults with perhaps unanticipated fault modes
- We need understanding of behavior of deteriorated components to develop capability to anticipate failures/predict remaining RUL
Background

Integrated Avionics systems consists of:
- Global Positioning System (GPS) module
- Integrated navigation (INAV) module combines output of the GPS model and Inertial measurement unit
- Power Supply module
- Typically step down DC-DC converters (22V-28V I/P – 5V O/P)
  - Important in portable electronic devices, which derive their power primarily from batteries.
Approach

1. Identification of failure modes and their relationship to their particular failure mechanisms
2. Identification of precursors to failure which play an essential role in the prediction of remaining life
3. Development of accelerated aging systems to allow the exploration of different failure mechanisms and aid the understanding of damage progression
4. Development of degradation models based on the physics of the device and the failure mechanisms
5. Development of remaining life prediction algorithms that take into account the different sources of uncertainty while leveraging physics-based degradation models that consider future operational and environmental conditions
Power Supply Degradation & Failures

- Electrolytic capacitors and MOSFET’s have higher failure and degradation rates among all of the components in DC-DC converter systems.
- The failure in these components can be attributed to a variety of factors.
- Degradation can be attributed to thermal and electrical stresses or just deterioration in the component due to long use.
Converter Performance

- Degraded capacitors affect the performance and efficiency of the DC-DC converters in a significant way
  - Increase in ripple current at output
  - Decrease in output voltage

- This work involves a method for studying the degradation effects of electrolytic capacitors and their impact on overall system performance.
Electrolytic Capacitor Degradation

- Continued degradation of the capacitor leads the converter output voltage to also drop below specifications.
- In some cases the combined effects of the voltage drop and the ripples may damage the converter itself.
- Affect downstream components leading to cascading faults in the system.
Degradation Mechanisms

- **Causes/Failure Mechanisms**
  - Electrolyte Evaporation
  - Degradation Loss of capacitance
    - Anode foil
  - Degradation of Oxide Film
  - Degradation Loss of capacitance
    - Of Cathode foil

- **Failure Mode**
  - Decrease in Capacitance
  - Increase in ESR

- **Causes/Failure Mechanisms**
  - Aging in the dielectric material
  - Electrolyte Evaporation
    - Over Voltage Stress
    - Excess Ripple Current
    - Charging/Discharging Cycles
    - High Ambient Temperature
  - Degradation Loss of capacitance
    - Anode foil
    - Over Voltage Stress
    - Excess Ripple Current
    - Charging/Discharging Cycles
    - High Ambient Temperature
  - Degradation of Oxide Film
  - Degradation Loss of capacitance
    - Of Cathode foil

- **Failure Mode**
  - Decrease in capacitance
  - & Increase in ESR
Capacitor Degradation Experiments

♦ Degradation in electrolytic capacitors depends on operating conditions – we consider thermal and electrical stressors

♦ Thermal and Electrical stressors elevates internal core temperature.
  ➢ Failure Mechanism: Electrolyte evaporation, Aging, Foil degradation
  ➢ Result: ESR increases gradually and capacitance decreases.

♦ Aging Experiment
  ➢ Run experiment, collect degradation data
  ➢ Estimate model parameters, validate model
Accelerated aging

- Allows for the understanding of the effects of failure mechanisms, and the identification of leading indicators of failure essential for the development of physics-based degradation models and RUL prediction

- Electrolytic capacitor 2200uF, 10V and 1A
- Thermal overstress > 2500 hrs
- Electrical overstress >200 hrs
  - Square signal at 200 mHz with 12V amplitude and 100 ohm load
Ageing Method

- In prognostic analysis we predict the behavior of the component using condition based monitoring.
- Under normal operating conditions the device lasts for several years and the process of condition based monitoring becomes difficult.
- In these experimental setups the devices are subjected to higher stressors like high voltage, temperature etc which degrade the device significantly.
- If tasked properly then accelerated ageing tests can give us degradation targeted to a particular failure.
Ageing Method

- Data from regular monitoring of the parameters can then be used for prognostic algorithms for calculating the RUL under certain operating conditions.
- Simulating certain accelerated conditions and monitoring the degradation systematically can be used for prognostic studies.
- In this work we subjected capacitors to high electrical stress with a specific charging/discharging cycle to observe the degradation over an operation period.
Set of 6 capacitors subjected to temperature of 125°C.
Thermal cycling done at the interval of every week.
Total time: 2800 hours.
EIS Measurements

The impedance measurements are taken using the Electrochemical Impedance spectroscopy (EIS) instrument.

Percentage decrease in Capacitance

All the capacitors in the set are characterized every 100-150 hours in the thermal chamber.

The ESR and capacitance values are calculated from the impedance values measured after characterization.
In all six capacitors were subjected to test simultaneously on each board.
**DAQ measurements**

- Initially the capacitors charge/discharge simultaneously but as time progresses, ESR increase varies for each capacitor this affects the RC-time constant.
- Monitored by taking the voltage measurements
- A temperature sensor was connected to the bare aluminum part on the top of the can (body) along with a sensor to monitor the surrounding room temperature.

![Schematic for the Data Acquisition Signals](image)

**Schematic for the Data Acquisition Signals**

**Custom Module PCB developed for Signal Amplifier Hardware**
Characterization

- All the capacitors in the set are characterized every 48-60 hours of operation.
- As the capacitor degrades the plot shifts to the right as ESR increases and capacitance decreases.
Degradation on lumped parameter model

$\begin{array}{c}
\text{C and ESR are estimated from EIS measurements} \\
\end{array}$

$\begin{array}{c}
\text{Degradation on lumped parameter model} \\
\end{array}$

$\begin{array}{c}
\text{Degradation on lumped parameter model} \\
\end{array}$

$\begin{array}{c}
\text{Degradation on lumped parameter model} \\
\end{array}$
Empirical degradation model

- Based on observed degradation from capacitance parameter
- Using Cap #1-5 data to estimate degradation model parameters
- Assumed exponential model based on capacitance loss
- Parameter estimation with least-squares minimization

\[ C_k = e^{t_k} + b \]
Empirical degradation model

\[ a = 0.0163 \]

\[ b = -0.5653 \]
Prognostics algorithm

- Implementation of prognostics algorithm with Kalman filter
- Capacitance loss considered as state variable
- EIS measurements and lumped parameter model used to obtained measured capacitance loss values
- Empirical degradation model used to generate the state transition equation
- Use Cap #6 to test predictions
- Failure threshold of 20% drop on capacitance based on MIL-C-62F
Kalman filter implementation

- State transition equation derived from degradation model

\[ \frac{\partial C}{\partial t} = \alpha C - \alpha \beta \]

\[ \frac{C_t - C_{t - \Delta t}}{\Delta t} = \alpha C_t - \Delta t - \alpha \beta \]

\[ C_t = (1 + \alpha \Delta t)C_t - \Delta t - \alpha \beta \Delta t \]

\[ C_k = (1 + \alpha \Delta_k)C_{k - 1} - \alpha \beta \Delta_k \]

- State-space model for filter implementation

\[ C_k = A_k C_k - 1 + B_k u + v \]

\[ y_k = h C_k + w, \text{ where} \]

\[ A_k = (1 + t), \]

\[ B_k = k, \]

\[ h = 1, \quad u = 1. \]
Capacitance loss tracking on Cap #6

- **Observed**
- **Filtered**

Aging time (hr)

Residuals (%)

Aging time (hr)
Prediction mode

- Assumed measurements are not available at some point in time
- Filter used in forecasting mode to predict future states
- Predictions done at 1 hr. intervals
- State transition equation used to propagate state (n: number of prediction steps, l: last measurement at t_l)

\[
\hat{C}_{l+n} = A^n C_l + \sum_{i=0}^{n-1} A^i B
\]
Remaining Useful Life Results

<table>
<thead>
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<th>RUL forecasting time (hr)</th>
<th>RUL estimate (hr)</th>
<th>Ground truth (hr)</th>
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<tr>
<td>0</td>
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<td>171</td>
<td>8.94</td>
<td>13.24</td>
</tr>
</tbody>
</table>

at t=139hr

at t=171hr
Conclusion and Future Work

- This work discussed proposes a model-based approach to study electrolytic capacitor degradation in DC-DC converters.
- The physics of failure model derived expressed the change in ESR values as a function of applied voltage for given operating conditions.
- In our experiments we are:
  - developing a systematic method for predicting this ageing time of components.
  - were able to map physics of failure models with a quantitative
- In future we plan to conduct experiments at different voltage stress conditions and observe the degradation effect with respect to change in electrical parameters and leakage current based on POF models.