A PoF based methodology to assess the reliability of a sensor module operating in harsh industrial environments

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Abstract

This paper presents the use of physics of failure based methodology in combination with finite element analysis (FEA) to assess the reliability of electronic assemblies. Mechanical loads such as vibration, shocks are one of the important causes behind electronic assembly failure and understanding behavior of the PCB and components under vibration is crucial to assess the reliability of the product. In this paper, condition-based monitoring sensor used in high-speed industrial machines is selected to perform a vibration analysis. First step of the reliability assessment is the failure mode and effect analysis (FMEA) which is a systematic and pro-active method to identify where and how system may fail and analyze the impact of the failures. FMEA study identified the critical components in sensor design such as a supercapacitor, a 40 pin QFN package, a LGA Network module and a standard battery. Finite element model of sensor assembly is built with a commercial software MSC Apex. Modal analysis extracts the first natural frequency as 256 Hz and shows mode shapes for the assembly. Harmonic analysis concludes that supercapacitor is the most vulnerable component under vibration and supercapacitor solder joints as well as leads will see a mechanical fatigue throughout the operation. Estimated fatigue life of the supercapacitor leads and solder joint is > 30 years and lifetime estimations are based on the lifetime model developed in house. It is pertinent to note that combination of FMEA and finite element analysis provides a quick and an efficient way to assess the reliability of the product in its early design stages.

1. Introduction

In recent years several reliability challenges have been emerged due to the modern electronic systems with advanced integrated circuits, miniature components, multilayer PCBs, and complex assembly processes. Along with the advancement of the technology reliability assessment methods were also evolved, and significant research has been conducted throughout the years to find out the time efficient reliability assessment techniques.

MIL-HDBK-217F [1] was developed in 1960's to provide a common basis for reliability predictions of military electronic systems. But limitations and inaccuracies [2][3] of MIL-HDBK-217F led to development of alternative methods such as Physics of Failure (PoF), Field data and Test data methods [4]. PoF models studies probable failure causes involved in any system and predict the reliability of the system or an individual component analytically without any historical data. FMEA is the first step in a PoF based evaluation and it provides a relationship between environmental loading conditions and failure modes of the system. FMEA focuses on finding a weak part in a system and failure mechanisms associated to this part which would provide a basis to improve the design for better reliability. Although a small system could have a complex FMEA matrix with hundreds of mode-effect records and such a large, complicated matrix will cost a serious amount of the time for an analysis and makes it very difficult to find the weakest part in the system.

Once FMEA has identified the weak parts, next step is to improve the design to address the most severe failure modes and rectify the system design. The improved design is further assessed either by building a prototype and performing accelerated life tests [5] or with the help of detailed FE model. Several researchers demonstrated the use of FEA to predict the response of the system to environmental loading conditions [6][7] and pointed out that modelling allows to predict the response much faster with considerably small analysis time compared to actual accelerated tests.

This paper proposes an integrated method to assess the reliability of the condition based monitoring sensor using FMEA and FEA. Figure 1 shows the implementation of the integrated method and stepwise process flow for reliability assessment. Initially FMEA analysis evaluates various environmental conditions and identifies the failure mode associated with components, PCB, and electronic assembly. Later detailed FE model is developed based on identified weak parts and FEA carried out to pinpoint the failure locations and extract stresses, strains at these critical locations. Objective of the FEA is to predict the behavior of the system for various design modifications and to estimate the lifetime of the system using lifetime models [8].

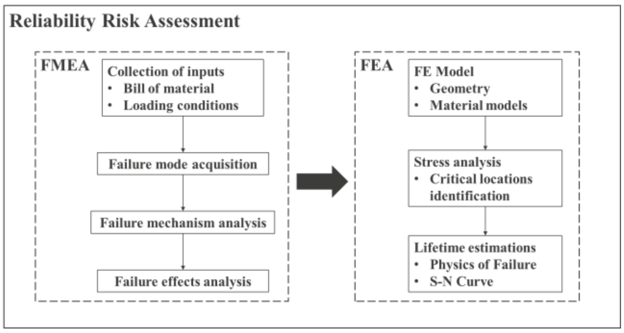


Figure 1. Implementation of integrated method

2. Sensor Construction

More and more IIoT (Industrial Internet of Things) modules are mounted on the machinery to monitor its performance. These modules are preferably providing their own energy allowing them for not having any wiring over the complex machines. Such a module is typically an electronic assembly consisting of electronic components mounted on printed circuit board (PCB) and PCB placed inside mechanical housing to protect it from surrounding environment. Main challenge while designing such a module is that the design should be robust enough to protect the electronics from harsh industrial conditions, but it should also allow energy harvesting for continuous monitoring and data transfer. Figure 2 shows the condition based monitoring sensor mounted on a bearing axis.

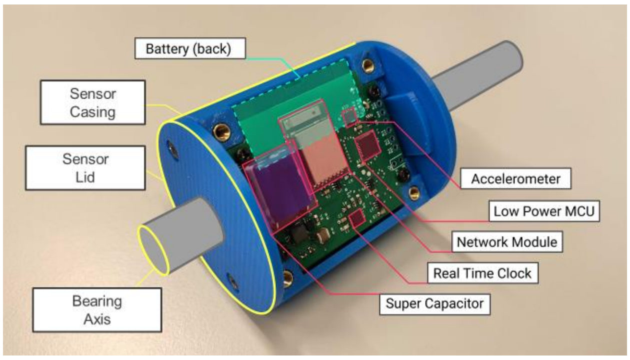


Figure 2. Condition based monitoring sensor

3. Failure Mode and Effect Analysis (FMEA)

FMEA is a systematic and pro-active method to identify potential failure modes and their causes and analysis describes the effect of these potential failures on individual component as well as complete system [9][10]. FMEA is a technique design to:

- Identify weak parts in a system and linked failure modes and their causes and effect of these failures on product reliability.
- Assess the impact of the different failures and prioritize failures based on risk factor.
- Execute corrective action to mitigate severe issues.

FMEA approach characterize each failure mode based on three risk factors, Detectability (D), Severity (S) and Occurrence (O). Every risk factor has its own categories and ratings and it defined by IEC standard 60812:2006 [9]. Risk priority number (RPN) is calculated based on these three risk factors as shown in equation 1[9]. Higher RPN number for a failure mode represents higher risk for the system reliability.

$$RPN = D \times S \times O \qquad (1)$$

Apart from RPN number criticality is also calculated based on severity and occurrence and it is given by equation 2. Criticality number defines the wear out behavior of individual components or the system. The detectability of wear-out or overstress failures is by default nearly impossible since it usually starts from a perfect structure which degrades over time by either normal operation (wear-out) or by unexpected overloading.

$$\text{Criticality} = S \times O \qquad (2)$$

Flowchart in figure 3 shows the process flow in FMEA analysis performed on condition based monitoring sensor [9][10]. Once RPN number is calculated for every possible failure mode, action plan is developed to reduce the highest RPN number. Following the action plan, corrective actions such as design modifications, replacement of components, manufacturing process changes are carried out to modify the complete system and FMEA analysis is reiterated until the system meets the reliability criteria. Final FMEA report consists of list of all critical components and failure modes ordered by their RPN ranks and it also provides a course of action to mitigate the risk.

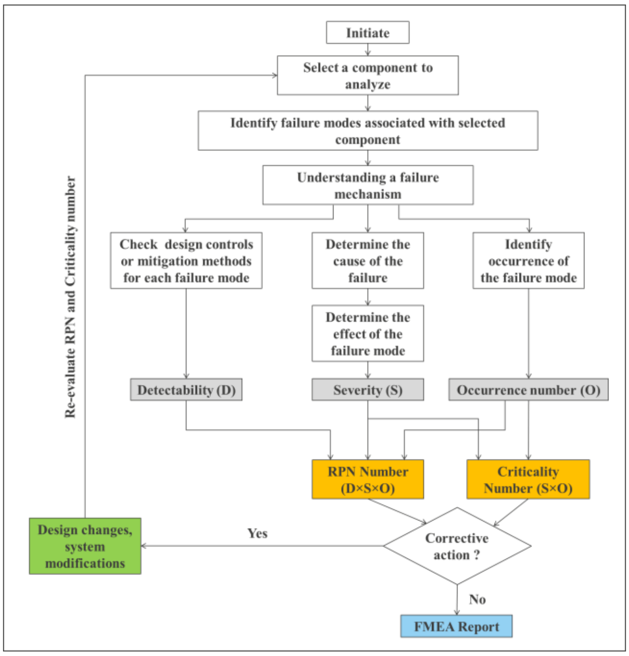


Figure 3. FMEA Flowchart

Figure 4 shows the excel based FMEA tool developed in house. This tool focuses on electronic system reliability and consists of a broad database of failure mode-effect matrix for various electronic components, PCBs, and assemblies. Tool is developed over the years based on extensive accelerated life tests and failure analysis performed on electronic assemblies and tool is kept up to date in accordance with emerging technologies.

Failure mechanisms	What to know about it		Risk assessment					Risk Mitigation	Affected Component
	Failure Mode	Failure Cause	D	S	O	DxSxO	SxO		

Figure 4. FMEA Tool

For a sensor operating in harsh industrial environment, it has been known that vibration and temperature are the two most dominant loading conditions. But for a sensor module shown in Figure 2, it has been identified that sensor will operate in temperature controlled environment and only dominating factor will be vibration. Long term exposure to small amplitude vibrations will lead to mechanical fatigue which will degrade the components and assembly over the time and eventually becomes a reliability hazard. Therefore, failure modes associated with vibration are focused during FMEA study and other failure modes are kept aside as these failures are not expected throughout the operation of the sensor.

FMEA tool classifies the failure modes into early failure based on RPN number and wear out failure based on criticality number. Table 1 shows few columns of the FMEA tool listing top three early failures which are associated with PCB and PCB assembly. Most of the early failures arises due to inaccurate assembly processes and poor process conditions. As seen in FMEA matrix, soldering process and laminate properties are strongly coupled and wrong combination of soldering process and board finish will produce flawed solder joints which will cause a severe reliability issue.

Table 1. FMEA report (Early failures)

Failure Mechanism	Failure Mode	RPN (D×S×O)	Affected Part
Delamination during soldering	Open contact	180	PCB, MCU, Network module, RTC
Poor solderability, wetting	Open contact	84	Solder joints
Excessive voiding	Open contact, Fracture	48	Solder joints

Detectability of early failures is high and there are several ways such as visual inspection, design rule check, qualification tests to increase the detectability. In contrast, wear out failures are very difficult to detect and shows complex failure mechanism as failures occur over the time. Therefore, FMEA focuses on the severity and occurrence of these failures which consequently provides the criticality number. Table 2 shows some of the identified wear our failures and for all of them the failure cause is the vibration fatigue. Vibration fatigue causes the cracks in solder joints and components leads which will eventually develop into a full fracture and functional failure at the component.

Table 2. FMEA report (Wear out failures)

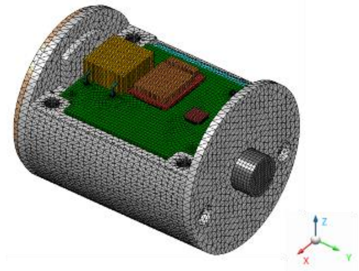
Failure Mechanism	Failure Mode	Criticality (S×O)	Affected Component
Vibration fatigue	Short circuit, open contact	81	Supercapacitor, MCU, Network module, Battery
Lead cracking	Open failure	54	16 pin SOP,
Cracking	Pin break	48	Crimp style connectors
Mechanical abuse	Internal short	45	Coin cell battery, 6V battery
Fracture	Functional failure	36	Plastic enclosure

FMEA has identified the 4 weak components in the sensor assembly: Supercapacitor, Network module, 40 pin QFN package (MCU) and standard 6V battery. And out of these 4, super capacitor turns out to be most vulnerable component because of the bent leads and it is placed in the vicinity of the PCB edge and fixation points. Apart from the supercapacitor, solder joints at network module and QFN package are also vulnerable to mechanical fatigue. FMEA report provides an immensely valuable information to develop a corrective course of action to improve the reliability of the product.

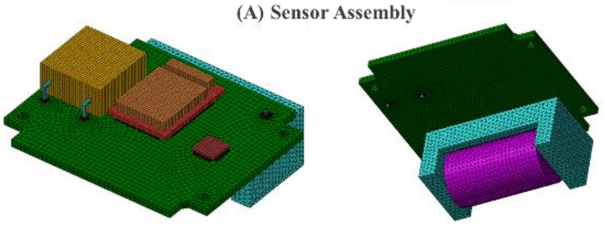
4. Finite Element Analysis (FEA)

A finite element model (FEM) is developed based on the gerber data of the PCB assembly and CAD files of the sensor enclosure to build the FE model close to real sensor. Commercial finite element software MSC Apex [11] is used to perform the modelling and simulation of the sensor.

Figure 5 shows detailed FE model of the sensor along with the mesh. Only 4 weakest components identified in FMEA report are modelled in detail along with PCB and enclosure. For the components and PCB, hex elements are used as hex mesh produces high quality results with fewer element compared equivalent tetrahedral mesh. Although sensor enclosure and battery are meshed using tetrahedral mesh as it captures curved surfaces precisely. Most critical part under vibration is the solder joints and leads of the components and mesh is refined at these critical locations to capture the effect of vibration accurately.



(A) Sensor Assembly



(B) PCB Top Side (C) PCB Bottom Side

Figure 5. FE Model with mesh

Alike mesh, materials properties are the indispensable input for any FE simulation and Table 3 lists all the materials used in the vibration simulation. All the materials are modelled as an isotropic material.

Table 3. Material properties

Component	Material	Density (Kg/m^3)	E modulus (GPa)	Poisson’s ratio
Die	Silicon	2330	112	0.28
Capacitor	Ceramic	2000	300	0.3
PCB	FR4	1850	31.5	0.18
Solder	SAC305	7380	42.75	0.33
Enclosure	PMMA	1180	2.9	0.35
Bearing axis	Steel	8000	193	0.27
Battery Holder	Nylon46	1180	1.2	0.4
Battery	Lithium	534	68	0.32
Leads	Copper	2000	117	0.21

4.1 Modal Analysis

Every object has a resonant frequency at which the object can vibrate naturally. At natural frequency, object will allow the transfer of energy from one form to another with minimal loss and amplitude of the response increases to infinity. Therefore, Modal analysis is performed initially to determine natural frequencies and mode shapes. Mode shapes provides a valuable information about dynamics of the sensor assembly. Table 4 indicates the top six natural frequencies.

Table 4. Natural frequencies

Mode Number	Frequency (Hz)
1	259
2	1008
3	1469
4	1587
5	2434
6	2932

It has been observed that first two modes are associated with supercapacitor followed by next two modes associated with bearing axis and later PCB bending occurs at mode 6 at 2932 Hz. Board bending is well known failure cause behind solder joint cracking and there are multiple failure modes associated with board bending movement. Figure 6 shows 1st and 6th mode shape of the sensor assembly.

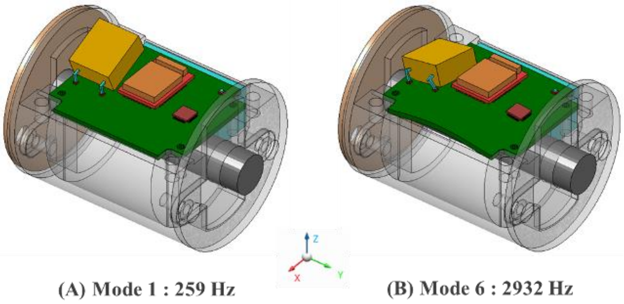


Figure 6. Mode shapes: (A) Mode 1 - supercapacitor out of plane motion (B) Mode 2 - PCB bending

4.2 Harmonic Analysis

Modal analysis is typically followed with harmonic analysis to understand the dynamic response of the system for a specific cyclic vibration load. Harmonic analysis allows to extract the stresses generated at critical locations for the cyclic load which will be used further to predict the fatigue life of the component.

Sensor assembly is connected to bearing axis by screwing top lid of the enclosure to the metal flange to avoid any sliding or the rotation of the sensor around bearing axis. Throughout the operation sensor will experience the small amplitude vibration load in lateral plane. Figure 7 shows the boundary conditions used in harmonic simulations along with sinusoidal simple harmonic loading condition. Based on field vibrations measurements, harmonic vibrations of 100 Hz frequency and peak displacement amplitude of 31.8 µm are used as a loading condition. This loading condition represents the worst case scenario for this assembly.

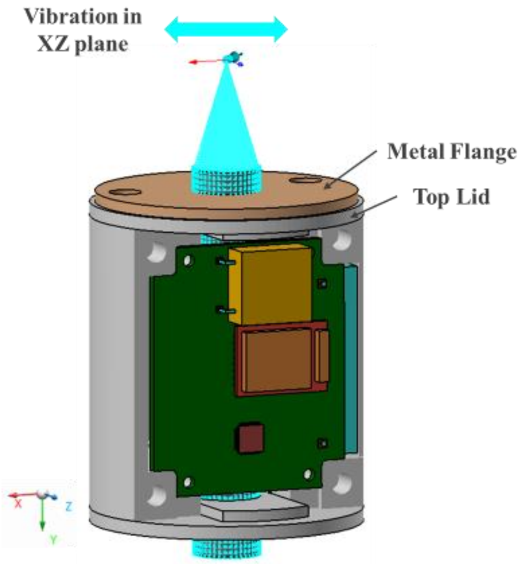
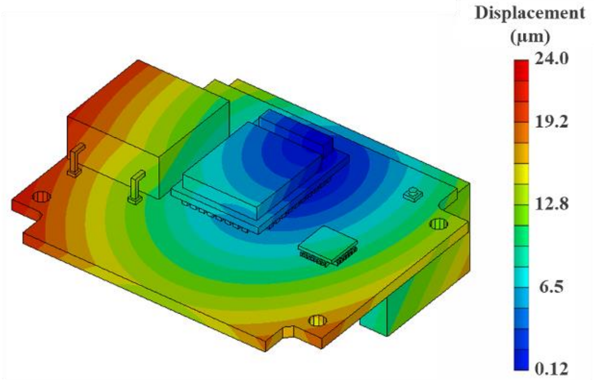
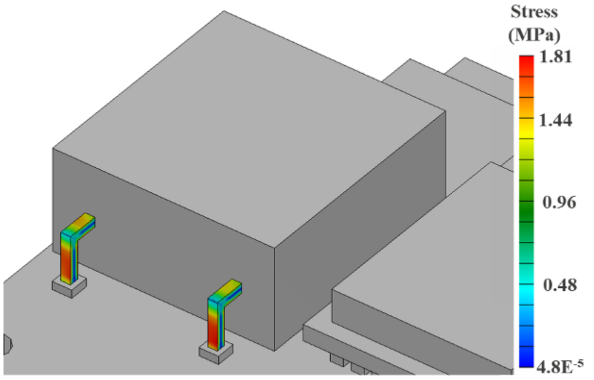


Figure 7. Boundary conditions for harmonic analysis

Harmonic simulation shows that highest stress appears at the supercapacitor leads and solder joints as the frequency of vibration is close to 1st natural frequency which is linked to supercapacitor. Although both copper leads and solder joints shows only elastic deformation. Figure 8 shows displacement plot for the PCB together with Von Mises stress at supercapacitor leads and solder joints. Highest stress concentration is observed at the location where leads are bent. It should be noted that board bending is negligible for 100 Hz vibrations while supercapacitor is lifted upward by 24 µm at peak displacement amplitude as 1st mode shape shows out of plane movement of the supercapacitor.



(A) Displacement plot: Left side of the PCB raised by 24 µm



(B) Von mises stress at supercapacitor leads and solder joints

Figure 8. Harmonic analysis: (A) Displacement plot for PCB assembly (B) Von mises stress at supercapacitor bent leads

Finally fatigue life of the supercapacitor copper leads is estimated using high cycle fatigue model developed by Basquin-Coffin-Manson. Equation 3 is a generalized power-law model where $\Delta\varepsilon$ is the total strain, E is the elastic modulus, ε'_f is the failure strain, b and c are fatigue constants and N_f is the cycles to failure. It provides a relationship between total strain and number of cycles to failure. Fatigue model constants along with the mechanical properties are determined iteratively by matching S-N curve to the failure data from experiments [8].

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \qquad (3)$$

Along with copper fatigue, solder fatigue life is also estimated based on in-house fatigue model developed during earlier studies. Table 5 shows stress and strain values at supercapacitor and lifetime estimations for both copper leads and solder joints. Von mises stress at QFN package, network module and battery solder joints is considerably small compared to supercapacitor which results into substantially large lifetime for each of these components.

Table 5. Lifetime estimations for supercapacitor

	Stress (MPa)	Strain (%)	Lifetime
Solder	0.59	0.0024	> 30 years
Leads	1.81	0.0013	> 30 years

Based on harmonic analysis, several design improvements were made in the sensor design to make product even more reliable. One of the important improvements was the addition of glue layer below supercapacitor. Glue below supercapacitor suppresses the out of plane motion of the supercapacitor and 1st natural mode occurs at 1467 Hz frequency. This improvement also reduces stress concentration at supercapacitor leads and fatigue life of the supercapacitor increased significantly (>> 30 years).

5. Conclusions

The focus of this paper is to provide a systematic way to assess the reliability of the electronic assemblies operating in harsh environmental conditions. Reliability assessment methodology integrates classical FMEA with modern FEA to understand physics of failure and to predict the lifetime of the system. Only classical FMEA cannot anticipate all the reliability issues with modern electronic systems and cannot assess all the failures associated with complex working environment. FMEA matrix for such a system can be extremely complex and it will cost a tremendous amount of time to analyze every failure mode. FMEA study followed by FEA saves a lot of time as FEA helps to study the design virtually without manufacturing actual prototype. Design improvements can be easily incorporated in FE model and their effects on the reliability of the system can be studied by simulating the model under specific loading conditions.

This study successfully evaluates the reliability of the IIoT sensor module under vibration using PoF based methodology. Initial FMEA study identifies the supercapacitor as the weakest part in the assembly and renders the failure modes associated with the supercapacitor. Later modal analysis concludes that 1st natural vibration occurs at 259 Hz, and it is coupled with the out of plane movement of the supercapacitor. At 100 Hz harmonic vibrations, supercapacitor tend to oscillate in vertical direction and as a results stress concentration is observed at the bent leads of the supercapacitor. Although only elastic deformations are observed at the leads and solder joints and lifetime estimations deduce that supercapacitor will survive more than 30 years under such a small amplitude vibration.

Further design modifications are planned for the sensor assembly to address the reliability concerns listed in FMEA and FEA reports. And next version of the sensor is expected to be more robust and reliable against vibrations and mechanical shocks.

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