INTERNATIONAL JOURNAL OF ADVANCE RESEARCH, IDEAS AND INNOVATIONS IN TECHNOLOGY

ISSN: 2454-132X
Impact factor: 4.295
(Volume 5, Issue 3)
Available online at: www.ijariit.com

Accelerated life testing of Electronic Control Unit

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ABSTRACT

An Electronic Control Unit (ECU) is an embedded system in automotive electronics that control one or more electro-mechanical systems or subsystems in a vehicle. For a sophisticated automotive will almost have 200 ECUs for multipurpose. Optimal Accelerated Life Test (ALT) Plan of Temperature Cycling (TC) and Mechanical Vibration (MV) for ECU are developed. TC is carried out as per IEC60068-2-14 (Nb) and MV was carried out as per IEC60068-2-64. Failure data is recorded and fitted to Weibull Distribution using Maximum Likelihood Estimation (MLE) in Minitab. Coffin and Manson Model (CMM) has been used to observe failures due to TC and Minor Fatigue Model (MFM) has been used to observe failures due to Random MV. Reliability and Life of the ECU are estimated and compared with Sherlock Simulation.

Keywords— *Electronic Control Unit, Accelerated Life Test, Maximum Likelihood Estimation, Coffin and Manson Model, Minor fatigue Model, Sherlock simulation, IEC60068-2-14, IEC60068-2-64, Reliability and life cycle*

1. INTRODUCTION

Now a day's fully automated auto motives dragging great attention of the world, which has to ensure safety for customers with perfect integrity of the system. There should be reliable Verification and Validation (VandV) methods for controls and actions while operating the integrated system. Electronic Control Unit (ECU) is a crucial component in the system for integration and control. Each ECU has a dedicated set of tasks for control action which activates system or subsystem. ECU is considered as a black box for Reliability Testing (RT) and for various other tests, it may be considered as a white box. Most of the ECUs are engine mounted there is great concern towards operating temperature and vibrations for which it has to withstand. The field data is given in table 1. So failure data is generated under stressed thermal and stressed vibration condition for sampled units. Various stages of ECU production is shown in figure 1.

Accelerated model is developed using Coffin and Mansion (CM) [7] Model which is a type of Inverse Power Law (IPL) Model. According to test plans, Thermal Cycling is conducted as per IEC60068 standard [14] for a specified number of failures. In a similar way, Mechanical Vibration test is carried out using Miner's fatigue modal [2] satisfying IEC60068 standard for a specified number of failures.

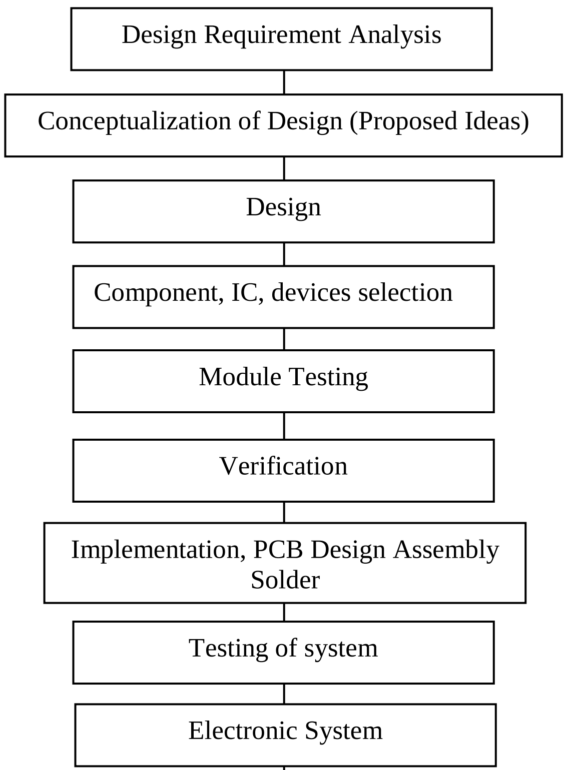

Fig. 1: Steps in production of ECU

Table 1: Field Temperature and Random vibration profile

	Operating Environment Specification		
	Underhood	**On Engine**	
	ECU	Sensor	ECU
Temperature Range, ˚C	-40 to 125	-40 to 175	-40 to 125
Vibration, g	Up to 3	Up to 40	Up to 10

2. ACCELERATED LIFE TESTING

The time available for testing is often considerably less than the expected lifetime of the component. In order to identify design weaknesses during testing one or more of the following may be necessary [12]

(a) Increase the number of units on test.
(b) Accelerate the number of cycles per unit of time (Accelerated Life Testing) and
(c) Increase the stresses that generate failures (Accelerated Stress Testing).

It is assumed that the number of cycles, stresses, hours, etc., to failures on the test, is proportionate to the acceleration factor that would be observed at a normal usage rate. The failures modes and their effects are assumed to be mutually exclusive [4]. Hence, combined reliability is simply the product of individual reliabilities. The following tests are done at constant stress and accelerated a number of cycles per unit time as per naming accelerated life testing [3].

(a) Thermal Cycling and
(b) Mechanical Random Vibration.

2.1 Thermal Cycling

2.1.1. Optimum Device-Hours (DH) and Standard Error: Optimum allocation of device-hours [13] for ALT plan is obtained from Minitab-18 with 65% Confidence Interval (CI) (well-known CI for early failures) furnished in Table 2. The Three stress levels are 110˚C, 150˚C and 180˚C with singly failure censored at right. Each interval holds 100 cycles with a duration of 150 hours with dwell time 30 minutes. Ramp rate is 10˚C/m and low temperature is -40˚C Standard error of the parameter of interest is 4.07513E-222.

Table 2: Best Optimum Allocations ALT plan.

Test Stress	Last Insp. Time	% Failure	% Allocation	Sample Units	Exp. Failures
110	2250	31.620	68.3333	16	5
150	1500	26.641	23.9583	5	1
180	1050	18.778	7.7083	1	1

Hence, the test is carried out for the same device-hours at the stresses mentioned.

2.1.2. Thermal Cycling Profile: Temperature Cycling Profile is obtained from IEC 60068-2-14-Nb as shown in Fig. 2 which satisfies the field life environment. The profile can be characterized by,

- High extreme temperature (Tmax),
- Low extreme temperature (Tmin),
- Temperature change ΔT, ΔT = Tmax – Tmin
- Ramp rates,
- Dwell times at extreme temperatures.

Profile loaded in the Thermal Cycling Chamber using iTools Software for 100 cycles are loaded as shown in figure 3.

2.1.3. (a) Coffin Manson Model (MFM): Coffin-Manson model [7] has mainly considered 2 factors, maximum temperature Tmax, temperature change ΔT. It has been mostly used for mechanical failure, material fatigue or material deformation, expressed as

$$N = B.\Delta T^{-b}.A(T_{\max}) \quad (1)$$

Where

N is the number of cycles to fail or Characteristic life of ECU,

ΔT is the temperature range during a cycle,

B is propositional constant,

b is temperature range exponent, the typical value is around 2 (for metals),

$A(T_{\max}) = e^{\left[\left(\frac{E_a}{K}\right)\left(\frac{1}{T_{\max}}\right)\right]}$ is an Arrhenius term evaluated at the maximum temperature T_{max} reached in each cycle,

K is Boltzmann's constant 8.623 x 10-5 eV/K and

E_a is Activation Energy.

Activation Energy EA is the most critical parameter. It can be determined by test.

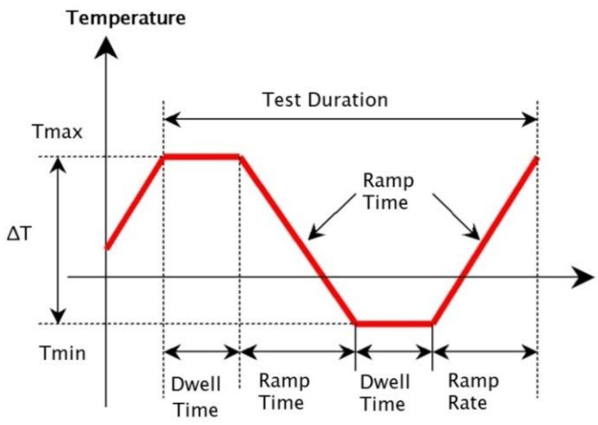

Fig. 2: Temperature cycle profile schematic

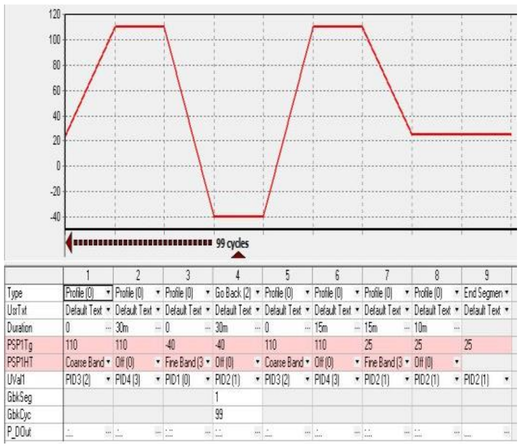

Fig. 3: Temperature cycle profile loaded in TC Chamber using iTools.

2.1.3. (b) Acceleration Factor (A_f) Calculation:
Calculation of A_f using Coffin-Manson Model [7]

Part 1 *Part 2*

$$A_f = \frac{N_{min}}{N_{max}} = \left[\frac{\Delta T_{max}}{\Delta T_{min}}\right]^b . e^{\left[\left(\frac{E_a}{K}\right)\left(\frac{1}{T_{kmax}} - \frac{1}{T_{kmin}}\right)\right]} \quad (2)$$

Where

Part 1 of the equation denotes the effects of change in temperature

Part2 of the equation shows the effects of the maximum temperature

N_{min} is the number of cycles to fail at the low-stress level temperature cycle,

N_{max} is the number of cycles to fail at the high-stress level temperature cycle,

ΔT_{max} is ΔT of the high-stress level temperature cycle,

ΔT_{min} is ΔT of the low-stress level temperature cycle,

T_{kmin} is the maximum absolute temperature at the low-stress level temperature cycle, in ºK and

T_{kmax} is the maximum absolute temperature at the high-stress level temperature cycle, in °K.

For this study, b=2 is used.

E_a is the most critical parameter and specifically related to certain failure mechanisms and failure modes. E_a was determined by correlating thermal cycling test data and the CMM [5]. In this case, the following steps are used and distribution plot data is presented in table 3.

A_f using test data from table 3

$$A_f \text{ -Test } TC_A \text{ vs. } TC_C = \frac{1980}{525} = 3.77143 \quad (3)$$

A_f using Coffin-Manson model

$$A_f \text{ -Model-}TC_A \text{ vs. } TC_C = \left[\frac{\Delta T_{max}}{\Delta T_{min}}\right]^b . e^{\left[\left(\frac{E_a}{K}\right)\left(\frac{1}{T_{kmax}} - \frac{1}{T_{kmin}}\right)\right]} \quad (4)$$

$$3.77143 = \left[\frac{220}{150}\right]^2 . e^{\left[\left(\frac{E_a}{86.23\mu}\right)\left(\frac{1}{383} - \frac{1}{453}\right)\right]}$$

Append equation (4) in (3), as above , then Activation Energy is determined to be: E_a=0.12.

Table 3: Distribution plot data.

TC Profile	Actual Failures	End Time	Cycle	Slope ζ	Life υ	Mean Life
TC_A	4	2250	1400	1.57	2636.68	1980
TC_B	2	1500	1000	1.94	1643.94	1275
TC_C	2	1050	700	1.98	1041.57	525

2.2 Mechanical Random Vibration

In recent trends, vibration fatigue accelerated testing methods have been vigorously under development. Moreover, the vibration loadings are typically restricted to sinusoidal or Gaussian random vibration, and the random vibration fatigue harm figuring depends on the presumption of Gaussian circulation. Fatigue test major concern is to generate Stress versus Number of cycles to failure (SN) curve which is of the form shown in figure 4.

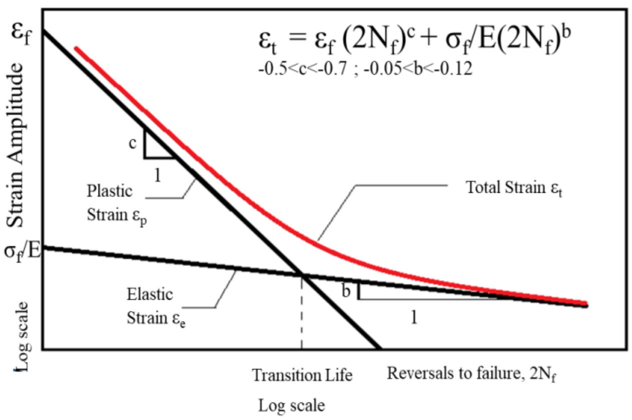

Fig. 4: Stress Vs Number of Cycles to failure Curve

Relationship between unreliability, stress, and strength is given in figure 5. Reliability is the overlapping area of stress and strength standard normal distribution curves [10]. Mathematically the relation is given by

$$P_f = \int_{-\infty}^{+\infty} f(\sigma)\left\{\int_{-\infty}^{s} f(S)dS\right\}d\sigma \quad (5)$$

Where

P_f is the probability of failure i.e., unreliability

f(σ) is the probability density function of stress

f(S) is the probability density function of the strength

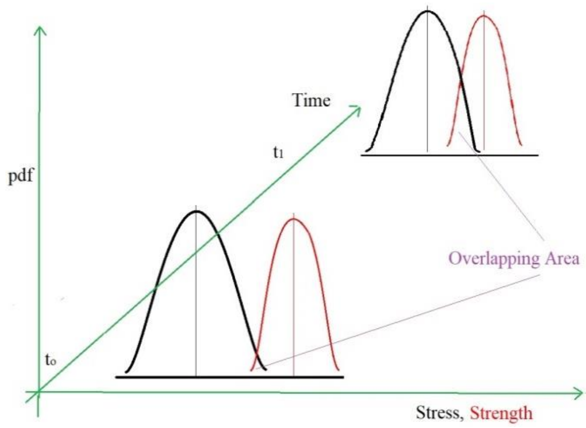

Fig. 5: Relation between Reliability Stress and Strength Curve

2.2.1 Minor Fatigue Model (MFM):

Through a series of derivations based on random vibration fatigue theory described in the literature [7], the fatigue damage under Gaussian random vibration [10] excitation can be calculated by

$$CFD = C_1 T_g \left[\frac{M_a(f_1)}{\zeta}\right]^{\left(\frac{z}{2}\right)} f_1^{\left(1-\frac{z}{2}\right)} \quad (6)$$

When CFD = 1,

$$T_g = \frac{f_1^{\left(\frac{z}{2}-1\right)}}{C_1}\left[\frac{\zeta}{M_a(f_1)}\right]^{\left(\frac{z}{2}\right)} \quad (7)$$

Where

CFD is cumulative fatigue damage, (Fatigue failure is generally regarded to occur if CFD=1.)

C_1 is proportional constant,

Tg is the duration of random vibration excitation,

z is the constant fatigue parameter that depends on the material of electronic components,

ζ is the equivalent damping ratio,

$M_a(f_1)$ is the magnitude of the acceleration PSD of the random vibration excitation at f_1 and

f_1 is the first-order natural frequency of electronic assembly.

Once the vibration excitation condition is determined, $M_a(f_1)$ and BW_i are also determined and can be also regarded as known parameters. f_1, ζ and BW_o can be obtained from the sweep sine test. Thus, there are only two unknown parameters (that is z and C_1) to be determined for the fatigue life prediction model described by Eqn. (6). The method to determine these two parameters is discussed below.

Priory one can solve the parameters z and C_1 based on the results of the random vibration fatigue test. As specified in Eqn. (7), the vibration fatigue consider two different Gaussian random acceleration excitations which are furnished respectively as:

$$T_{g1} = \frac{f_1^{\left(\frac{z}{2}-1\right)}}{C_1}\left[\frac{\zeta}{M_{a1}(f_1)}\right]^{\left(\frac{z}{2}\right)} \quad (8)$$

$$T_{g2} = \frac{f_1^{\left(\frac{z}{2}-1\right)}}{C_1}\left[\frac{\zeta}{M_{a2}(f_1)}\right]^{\left(\frac{z}{2}\right)} \quad (9)$$

Dividing (8) and (9) then,

$$\frac{T_{g1}}{T_{g2}} = \left[\frac{M_{a2}(f_1)}{M_{a1}(f_1)}\right]^{\left(\frac{z}{2}\right)} \quad (10)$$

Taking the logarithm on both sides of Eqn. (10)

$$\ln\frac{T_{g1}}{T_{g2}} = \left(\frac{z}{2}\right)\ln\left[\frac{M_{a2}(f_1)}{M_{a1}(f_1)}\right] \quad (11)$$

$$P = \left(\frac{z}{2}\right) Q \quad (12)$$

Based on the test results shown in table 4 a series of values of the group (P, Q) can be obtained and fitted to a straight line. Then the value of parameter z can be estimated from the slope of the line as 5.227.

Then the procedure to solve the parameter C_1 using the Eqn. (7) but transformed to:

$$C_1 T_g = f_1^{\left(\frac{z}{2}-1\right)}\left[\frac{\zeta}{M_a(f_1)}\right]^{\left(\frac{z}{2}\right)} \quad (13)$$

Given $R = f_1^{\left(\frac{z}{2}-1\right)}\left[\frac{\zeta}{M_a(f_1)}\right]^{\left(\frac{z}{2}\right)}$ and $S = T_g$

Eqn. (13) is simplified to $R = C_1 S$

Accordingly, a series of values of the group (R, S) can be obtained based on the test results and to be a straight line. Then the value of parameter C_1 can be estimated from the slope of the line as 1.27.

2.2.2 Acceleration factor (A_f) Calculation: Accelerated Mechanical Vibration Test (AMVT) is carried out using the Eqn. 14 for Sine test and Eqn 15 for Random vibration tes (14) for study n is 6.7.

$$A_{fs} = \left(\frac{s_1}{s_2}\right)^n \quad (15)$$

$$A_{fr} = \left(\frac{m(f)_1}{m(f)_2}\right)^{\frac{n}{2}}$$

Where
A_{fs} is Acceleration factor of sine test
A_{fr} is Acceleration factor of random test
s_1 is severity (RMS) at test condition,
s_2 is severity (RMS) at in-service condition,
n valve is based on the SN curve as in Fig. 4
$m(f)_1$ is PSD (g2/Hz) at test condition and
$m(f)_2$ is PSD (g2/Hz) at in-service condition.

2.2.3 Test Procedure: Before the random vibration fatigue tests, the transfer characteristics of the samples have been tested by a sweep sine test. Accelerometer must be placed on the unit under test. The profile loaded is a constant acceleration of 10m/s_2 with a bandwidth of 450 Hz, lower and higher frequency are 50 and 500Hz. Then determine the first-order natural frequency f_1 is 250 Hz, damping ratio ζ is 0.032 (Obtained from $BWo = 2\zeta f_1$), and the pass-band width of the specimen BW_o is 16 Hz.

Gaussian random vibration test is carried for the profile shown in table 4 which is as per IEC 60068-2-64. Mounting of the unit is the same as in field condition and the accelerometer position should be on slip table for X and Y axis and on head expander for the Z axis. A number of units dedicated for iteration is 3 and the failure time is mean of each individual unit failure time. Details are furnished in Table 5. A Sweep sine test plot of ECU is as shown in figure 6 Random Vibration test plot for the 3rd-row profile of ECU is as shown in figure 7.

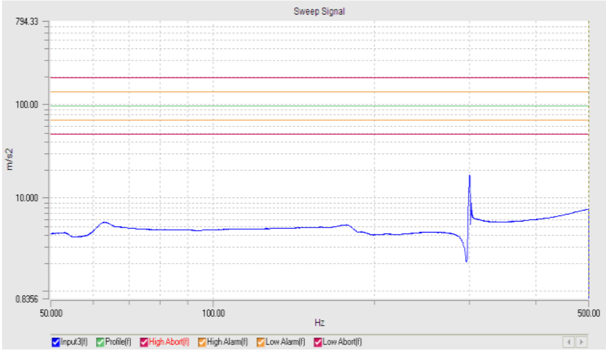

Fig. 6: Sweep Sine test plot of ECU

Table 4: Random vibration profile data

Iteration Number	Lower Frequency (Hz)	Upper Frequency (Hz)	PSD Bandwidth (Hz)	PSD Magnitude (g2/Hz)	Grms (g)
1	20	2000	1980	0.40404	20
2	20	2000	1980	0.32727	18
3	20	2000	1980	0.22727	15

Table 5: Failure Times of ECU

S. No.	Number of units	Failure Times (m)*	Mean Times (m) *
1	3	131, 114, 108	118
2	3	200, 183, 234	206
3	3	291,349,321	321

* rounded to a nearest higher integer

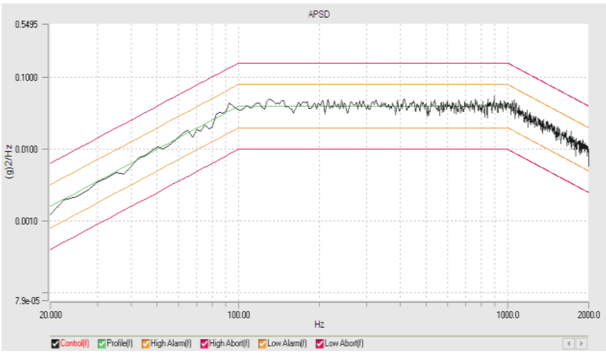

Fig. 7: Random Vibration test plot for the 3rd-row profile of ECU

3. DISTRIBUTION ANALYSIS

Data is best fitted in Weibull Distribution with Anderson-Darling Coefficient 49.266. Weibull Distribution is given by [6, 11]

$$R(t) = e^{-\left[\frac{t}{\upsilon}\right]^{\zeta}} \quad (16)$$

Where
R(t) is per cent succeeded (the probability of success) at "t" number of cycles or hours.
ζ is shaped parameter or Weibull slope.
υ is scale parameter or characteristic Weibull life.

MLE for Interval data is given by [8, 9]

$$\mathcal{L} = \sum_i \ln\left[F(\eta_{ij}) - F(\eta_{ij-1})\right] \quad (17)$$

Where
i is failure cycle number, i = 1,2,3,…….,I.
F is cumulative Weibull distribution function,

j is Inspection intervals and j = 100,200,…..,J.
η is the Inspection Right Interval (RI).
η = 150,300,….,H.

4. SHERLOCK SIMULATION

Sherlock Automated Design Analysis Software is Reliability Physics based electronics design reliability analysis tool that disentangles new item improvement. It mechanizes thermal cycling and mechanical vibration that democratizes the thermal and mechanical examination of hardware through limited component demonstrating and gives bits of knowledge which wiping out test disappointments and configuration defects. Sherlock fabricates emphases by for all intents and purposes running thermal cycling, control temperature cycling, vibration, stun, bowing, thermal derating, quickened life, characteristic recurrence, one can change structures in close continuous and accomplish capability at most speed.

4.1 Inputs Required

Archive uploaded for analysis is IPC 2581. That consists of assembly, Bill of Materials (BoM), copper layers, drill and fabrication details, etc. The major analysis is concentrated on the life cycle which is loaded with Thermal Cycling and Mechanical Vibration profile with reference to IEC 60068 standards. The number of cycles is limited up to the occurrence of failures by iteration. The partial layout of the ECU is shown in figure 8 this included a dominant list of parts.

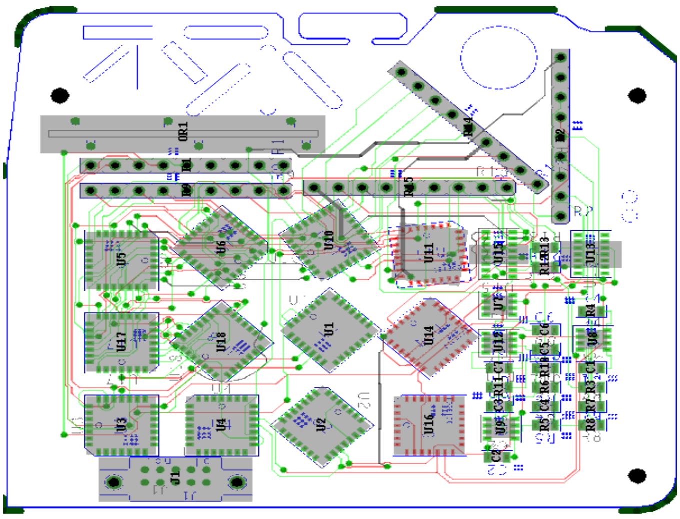

Fig. 8: Layout of ECU

4.2 Life Cycle Analysis

Thermal Cycling analysis has been done with input profile as shown in figure 9.

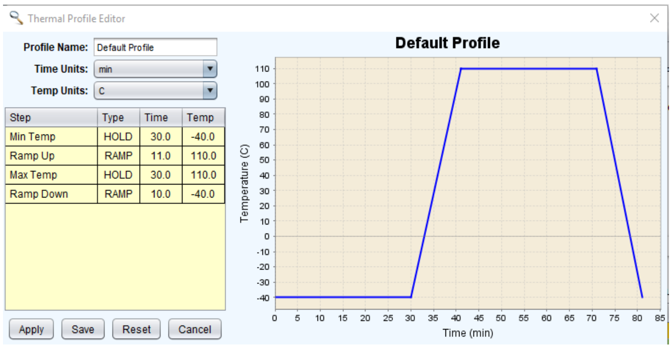

Fig. 9: Thermal cycling profile in Sherlock

Random vibration analysis is done with input profile as shown in figure 10.

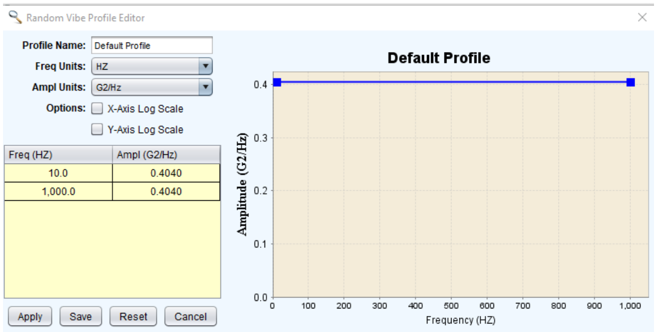

Fig. 10: Random Vibration profile in Sherlock.

Output generated by the Sherlock is a CAE virtual model of an ECU Board Assembly under vibration and thermal stresses and durability simulation produced Pareto list of failed components. Reliability of the ECU for both analyses is depicted in the graph shown in figure 16.

List of the components which are under risk is produced as Pareto list for thermal and vibration analyses shown in figure 11 and 12 respectively [1].

Fig. 11: List of components under risk due to thermal cycling shown in hot colour

Fig. 12: List of components under risk due to random vibration shown in hot colour

One can see both are similar but it won't be the case all time however if both are the same it would be easy to handle.

5. RESULTS

5.1 Result of Thermal Cycling

Reliability of the ECU for a life of 20 years that is for 8 cycles per day of the vehicle will be 0.999854 with 65% confidence interval is obtained. This result is only due to thermal cycling stress during normal life where other causes are assumed no effects on the component. Only a few effective read points were available in this study since continuous monitoring was not available as shown in figure 13. All parts needed to be removed from the temperature cycle chamber for the electrical test to be performed.

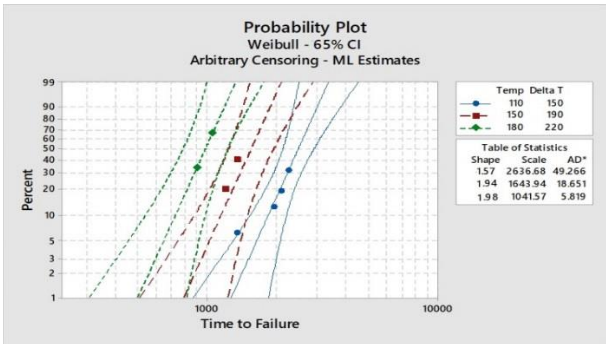

Fig. 13: Weibull plot of temperature cycle test data.

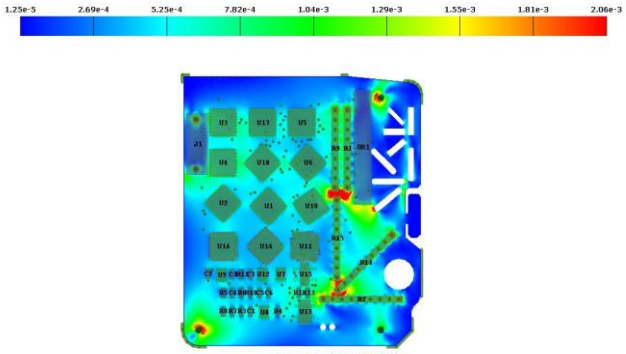

Fig. 14: Virtual Stress model for thermal cycling

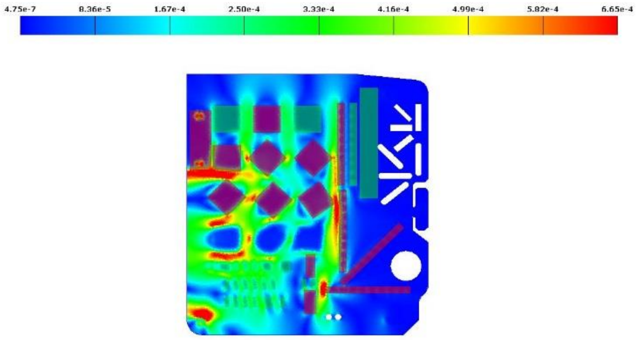

Fig. 15: Virtual Stress model for random vibration

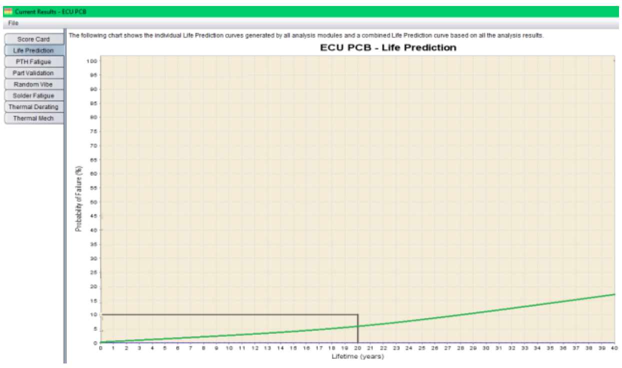

Fig. 16: Graph for the ECU with an expected life of 20 years with 10% Probability of failure.

5.2 Result of Random Vibration

Reliability of the ECU for a life of 20 years that is for 8 cycles per day of the vehicle will be 0.9989 is obtained. This result is only due to mechanical random vibration stress during normal life where other causes are assumed no effects on the component.

The failures modes and their effects are assumed to be mutually exclusive [4]. Hence combined reliability is simply a product of individual reliabilities i.e., 0.999854*0.9989 = 0.998754.

6. CONCLUSION

The Accelerated life testing of the ECU is done in the laboratory and the results are established and are compared with Sherlock Simulation. The analysis is done for specified device hours. Moreover the established results are based on a few environmental parameters. Testing procedures have been performed in the Laboratory. All data and test results presented in the document the equipment's characteristics which have been analysed and/or calculated at that specific point in time. All test data and results presented are only a partial representation of the total system which is tested. The results should not be considered a true representation of the complete system.

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