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Analysis of the Lifecycles of Automotive Resistor Lead in Random Vibration

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Abstract
The lifecycles of vehicular resistor lead in random vibration environment were analyzed in this technical note and the finite element model of a vehicular printed circuit board (PCB) was established. It is with two short edges of PCB fixed for boundary condition to simulate the actual working conditions of the vehicle driving on the road, the constrained modal analysis was simulated and experimental verification were carried out. Both the PCB and the vehicular resistor which soldered on PCB were excited vertically according to Standard GJB150. Based on simulated vibration excitation environment, the power spectral density (PSD) stress value of the resistor lead was calculated. The lifecycles of the resistor lead were calculated theoretically and were verified by following failure-oriented accelerated testing (FOAT). Finally, in order to extend the lifecycles of resistor lead, an improved solution for PCB is put forward.

Keywords Automotive electronics · Failure · Lifecycle · Vibration environment

1 Introduction

With the widespread application of automotive electronics, the reliability of electronic equipment in automobiles has emerged as a critical technical benchmark for assessing product performance. Enhancing the durability of automotive electronics has become a universally shared objective within both domestic and international sectors of the automotive industry [4, 6, 9, 11, 12]. In instances of electronic equipment failures attributed to environmental factors, the vibrational component constitutes 27% of the overall contributing factors [15]. Resistors integrated into automotive electronic equipment exhibit an 80% likelihood of failure, primarily attributed to PCB loop-breaking [14]. For automotive electronic components to operate reliably within a harsh, random vibration environment and fulfill the anticipated lifecycles, their design must align with standardized reliability requirements [5, 8].

As an essential load-bearing component, the vibration characteristics of the Printed Circuit Board (PCB) exert a significant influence on the lifecycles of resistor leads. The findings demonstrate a significant correlation in relation to natural frequencies, acceleration, and PCB strain, as well as time to failure and failure modes. A noteworthy association exists between cycles to failure and the modeling process [2, 7, 19]. To prevent resonant damage, it is imperative to avoid the resonant frequency of the PCB.

2 FEM Modal and Simulation Analysis for Vehicular PCB and Resistor

The dimensional parameters of Wenhua 1085 vehicular PCB are 215 mm x 115 mm x 1 mm. The material properties are listed in Table 1. The meshing and boundary conditions with two short edges fixed were shown in ANSYS in Fig. 1(a). The element type is SOLID 185. There were totally 75,733 meshing grids. The frequency of first, second, and third mode is 78.972 Hz, 127.57 Hz, 232.93 Hz respectively.

The vertical Power Spectral Density (PSD) curve representing the vibrational environment, as outlined in Standard GJB 150 (Fig. 1b), was incorporated into the ANSYS

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Table 1 The Parameters of PCB & Resistor

Parameter	Value
PCB Dimension	215 mm×115 mm×1 mm
PCB Density	1400 kg/m^3
PCB Poisson ratio	0.14
PCB Young's modulus	1.9 GPa
Resistor Lead Density	8900 kg/m^3
Resistor Carbon Core Density	2330 kg/m^3
Solder Joint Density	7300 kg/m^3

Random Vibration analysis. Consequently, the PSD response of the resistor lead was acquired (Fig. 1c). Subsequently, ANSYS calculated the PSD stress value at this specific point, yielding a result of 30.171 MPa, which was concurrently utilized to estimate theoretical lifecycles.

3 Vehicular PCB and Resistor Modal Testing

3.1 Equipment and Standard

The Scanning Laser Doppler Vibrometer (SLDV) was employed for the investigation of the mode frequency of the automotive PCB. The physical representation of the object is illustrated in Fig. 2(a), while the experimental procedure is depicted in Fig. 2(b).

The experiment adhered to the standards outlined in GJB 150.16 A-2009, which delineates the vibration testing methodology for military equipment laboratories, as illustrated in Fig. 3 [16]. The testing frequency spans from 1 to 100 Hz. This experiment primarily focuses on the vertical vibration characteristics of the PCB.

3.2 Modal Experiment Results

With the same boundary conditions, the upshots of SLDV exhibit that the frequency of first, second, and third mode for PCB & resistor is 81.50 Hz, 140.25 Hz, 238.00 Hz respectively.

Table 2 notes that the modal modes of the two methods are basically correspondent, and the maximum error of frequency is 9.04%. The results indicate that simulation is valid and solid.

4 Resistor Lead Lifecycles Calculation and Testing Verification

According to the S-N curve of the resistor lead obtained from the experiment (Fig. 4), the lateral axis is the number of cycles N and the vertical axis is the stress in the unit of MPa.

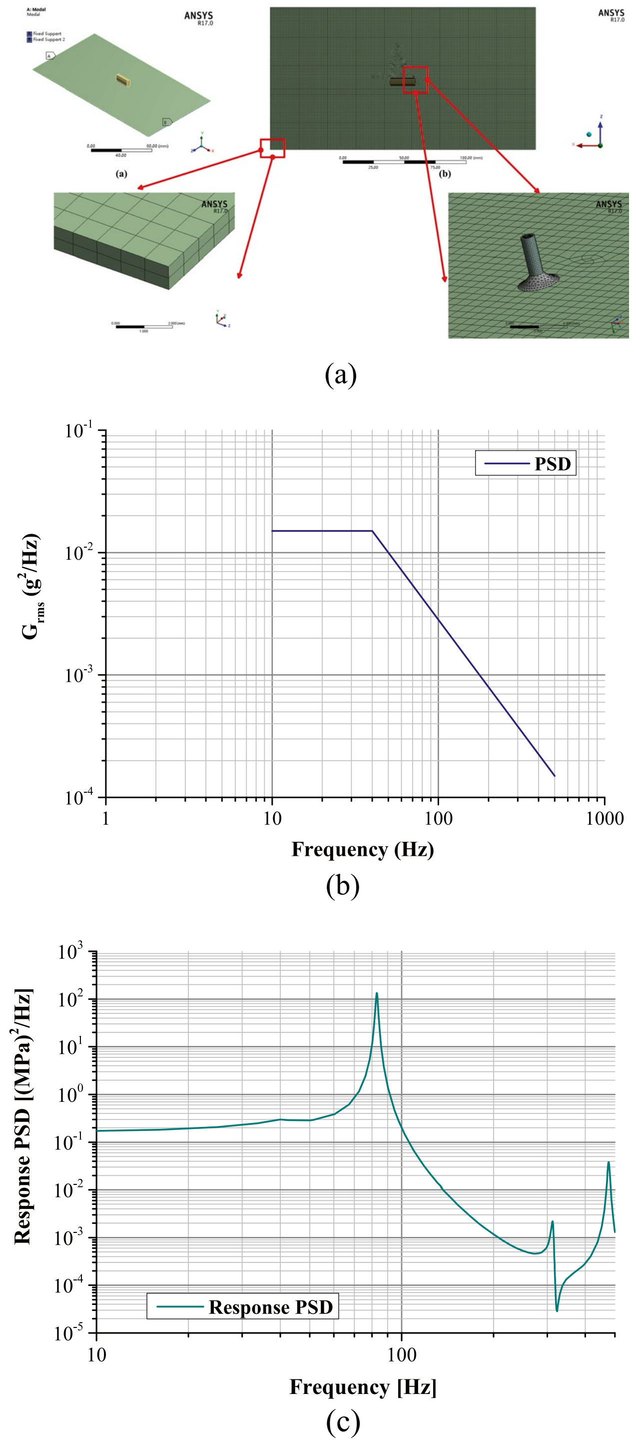
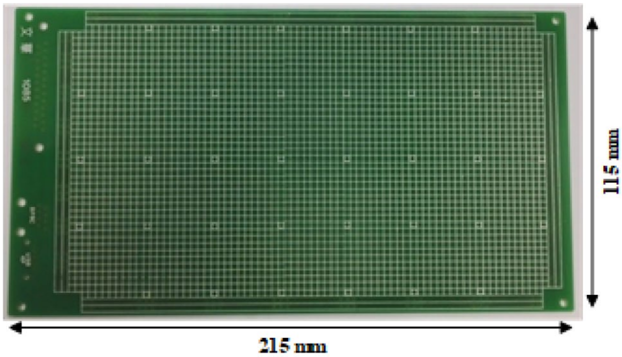


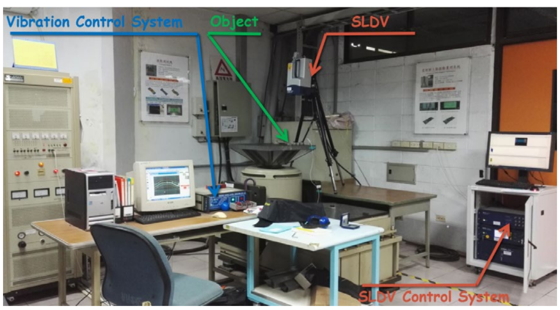
Fig. 1 **a** Boundary condition& Meshing; **b** Vibration Standard of Driving Vibration Environment in GJB 150; **c** Response PSD of Resistor Lead Stress

According to PSD stress value of resistor lead based on ANSYS Random Vibration [1].

$$S_1 = 3.0171 \times 10^7 Pa$$



(a)



(b)

Fig. 2 **a** Testing PCB; **b** Testing Situation

The formula (1) [15] can run the calculation about the number of stress failure lifecycles

$$N_1 = N_2 \frac{S_2}{S_1}^{b} \tag{1}$$

where:

N_1 = number of stress cycles needed to produce a fatigue failure.

$N_2 = 10^6$ cycles to fail at 200 MPa (reference point).

S_2 = 200 MPa (stress to fail at reference point).

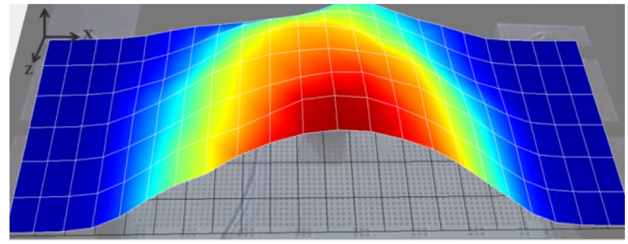
S_1 = 30.171 MPa (1σ RMS stress).

b = 6.4 (slope of fatigue line) [18].

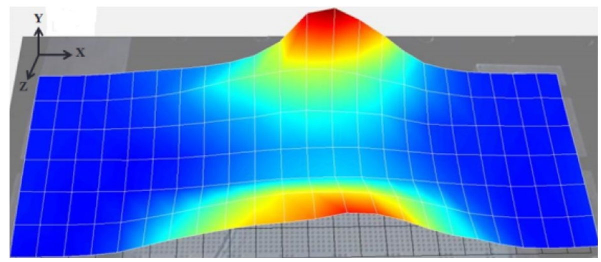
The number of stress failure cycles can be generated as follows:

$$N_1 = 10^6 \times \left(\frac{2.0 \times 10^8}{1 \times 3.0171 \times 10^7} \right)^{6.4} = 1.8081 \times 10^{11}$$

$$N_2 = 10^6 \times \left(\frac{2.0 \times 10^8}{2 \times 3.1041 \times 10^7} \right)^{6.4} = 2.141 \times 10^9$$



(a)



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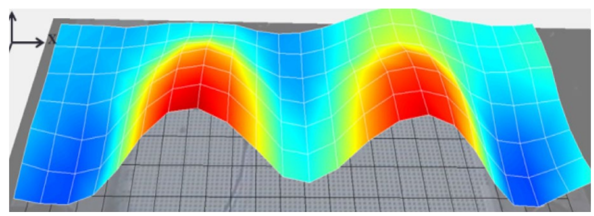

(c)

Fig. 3 **a** The First Mode Scanning of PCB; **b** The Second Mode Scanning of PCB; **c** The Third Mode Scanning of PCB

$$N_2 = 10^6 \times \left(\frac{2.0 \times 10^8}{3 \times 3.1041 \times 10^7} \right)^{6.4} = 1.5982 \times 10^8$$

According to the normal distribution, 68.3% of the time is consumed in the − 1σ~+1σ section; 27.1% of the time is engaged in the − 2σ~-1σ & 1σ ~ 2σ section; 4.3% of the time is occupied in the --3σ~-2σ & 2σ ~ 3σ Sect. 0.3% of

Table 2 Frequency Data of Testing and Simulation

	Testing Value(A)	Simulation Value(B)	Error:(A-B)/A
First Mode	81.50 Hz	78.972 Hz	3.1%
Second Mode	140.25 Hz	127.57 Hz	9.04%
Third Mode	238.00 Hz	232.93 Hz	2.13%

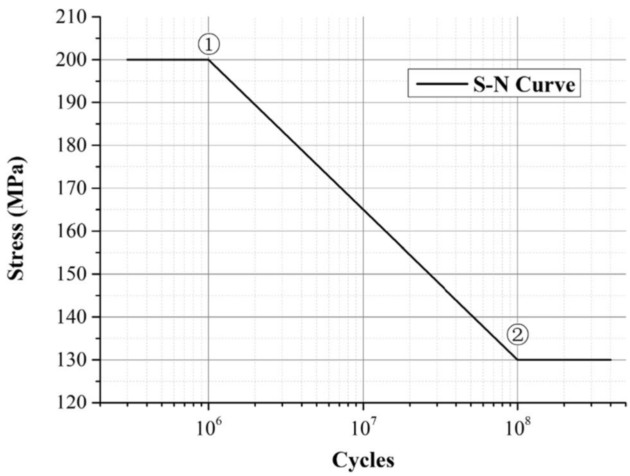

Fig. 4 Fatigue S-N Curve of Copper Wire

the time ranges outside $-3\sigma\sim+3\sigma$. The lower order modes could be excited by lower energy. The vibration of PCB in the first order mode is not only the most remarkable but also the vulnerable to lead. Therefore, the frequency of first mode [10], 81.5 Hz, is used in 1 h (3600 s) test to calculate the number of actual stress cycles as follows:

$$n_1 = 81.5 \times 3600 \times 0.683 = 2.0 \times 10^5$$

$$n_2 = 81.5 \times 3600 \times 0.271 = 7.95 \times 10^4$$

$$n_3 = 81.5 \times 3600 \times 0.043 = 1.27 \times 10^4$$

Miner's rule is broadly practiced in engineering to approximate fatigue cumulative damage.

$$R_R = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \cdots \tag{2}$$

R_R in formula (2) symbolizes the percentage of fatigue cumulative damage and 100% intends that it gets the critical point of failure. When the damage exceeds 100%, it means that the absorbed energy of the specimen reaches the upper limitation where fatigue failure occurs.

$$R_R = \frac{2.00 \times 10^5}{1.8081 \times 10^{11}} = \frac{7.95 \times 10^4}{2.141 \times 10^9} + \frac{1.27 \times 10^4}{1.5982 \times 10^8}$$
$$= 0.0001177$$

0.01177% of the lifecycles for vehicle resistor lead was expended after one hour in vibration environment. The theoretical lifetime of vehicle resistor lead was 8,496.2 h.

Subsequently, we directed the failure oriented accelerated testing (FOAT) of resistor in Fig. 5 with the resonant excitation of 4 g in numerical value and 6.4 in hardening coefficient [3]. Being recorded in Table 3, the fluctuation of resistance was measured by the digital multimeter of model CAT III 600 V.

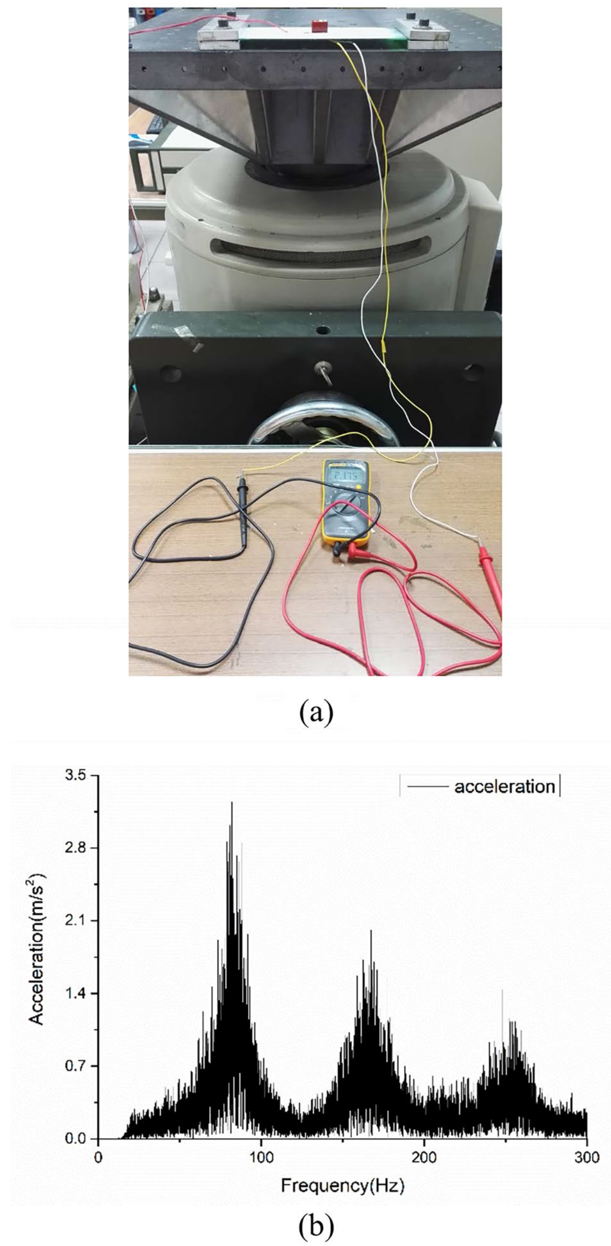

Fig. 5 **a** The failure oriented accelerated testing (FOAT) of resistor; **b** The acceleration test results

From 0 to 5,000 s, the resistance value is stable at 12.4 Ω ~ 12.6 Ω, fluctuating within 1 Ω, which could be attributed to environmental factors. When the time node is 5,220 s (1.45 h), the resistance value began to soar to 15.4 Ω. That matches the IPC-9701 A-2006 standard for the performance test and appraisal of surface mounted tin solders, and the fatigue failure of the resistor lead can be determined.

Table 3 The Relation of Between Testing Time and Resistance

Time (Seconds)	0	1800	3600	5220	5222	5224	5226	5228
Resistance (Ω)	12.4	12.4	13.1	15.3	13.7	15.4	15.3	15.4

According to formula (3), the resonant excitation test with constant frequency adjusts g value to complete the FOAT.

$$T_1 = T_2 \times \left(\frac{G_2}{G_1}\right)^{n} \tag{3}$$

where:

$G_1 = 1.04$ g (peak field test data).

$G_2 = 4$ g (peak proposed qualification test level);

$n = 6.4$ (vibration fatigue exponent).

$T_2 = 1.45$ (failure time in FOAT).

Therefore, the lifecycles of resistor lead T_1 from the vibration environment in GJB150 can be calculated out 8,045.2 h [13, 17].

In sum, the actual lifecycles of resistor lead are 8,045.2 h which is consist with the theoretical value of 8,496.2 h, the error between them is 5.61%.

5 Improvement for Damping Vehicle PCB

Aiming at the refinement of the weakness in automotive PCB of the first, second and third mode respectively, the improved scheme for extending the lifecycles of the resistor lead is to mount steel rib of 191 mm in length and 5 mm×1 mm in cross section on the PCB. The maximum stress of 1σ Von Mise on the resistor lead decreases from 34.725 MPa to 29.316 MPa by 15.6% after mounting 191 mm rib. The lifecycles of resistor lead can be extended by 86.7% to 15,862 h after improvement.

6 Conclusion

The current investigation examined the lifecycles of resistor leads in the random vibration environment of automotive systems. The primary observations derived from this study are summarized as follows:

1. Considering the parametric differentia of calculated results, the failure oriented accelerated testing (FOAT) of resistor lead in 4 g constant frequency resonance excitation environment occurred failure at 1.45 h which was converted to 8,045.2 h in 1.04 g random vibration environment. Compared with the theoretical value of 8,496.2 h, the error was 5.61%.
2. For the improved scheme about extending the lifecycles of resistor lead, 191 mm steel rib was mounted on the PCB to enhance the frequency of first mode of PCB. And the lifecycles of resistor lead were extended by 86.7%, reaching 15,862 h.

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Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interests The author declare that he has no conflicts of interest.

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