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Potential failure mode identification of operational amplifier circuit board by using high accelerated limit test

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ABSTRACT

In this study, the potential failure modes of a small operational amplifier circuit board were investigated. The high accelerated limit test (HALT) was employed to identify the failure modes under multi-axial vibration and temperature loadings. Five stress tests, specifically, low and high temperature, vibration, thermal shock, and composite profiles were performed. An aluminum electrolytic capacitor was damaged under the low temperature process, whereas the capacitance of a ceramic capacitor decreased under the high temperature process. The vibration test revealed that mechanical fatigue occurs at the terminal leads of aluminum electrolytic capacitors. The HALT also revealed coupled effects between high and low temperature processes and vibration.

1. Introduction

The Internet of Things (IoT) offers a new paradigm in the modern social system and the global market is expanding [1]. The major concern regarding the increasing number of connected devices is reliability of the electronic products. Reliability is the ability of an item to perform under expected performance requirements for a specified period in field-use conditions and the classic frequency approach is currently applied to ensure product reliability. However, the significant increase in the number of connected devices suggests that the classic approach will soon become ineffective; therefore, new technology to assess the reliability of systems is required.

Reliability tests are an effective way to verify the design of products. The thermal cycling test is a typical design verification test for interconnections such as solder joints. Thermo-mechanical fatigue of the interconnections is a major failure mechanism and the test conditions are also designed based on the target failure mechanism. However, even in cases where products passed the thermal cycling reliability test, failures have occurred in the field. This implies that some potential failure modes are beyond the scope of the reliability test employed. There are many components on a circuit board owing to the trend toward highly integrated technology in electronics. The potential risk of electronic products is consequently increasing.

The prognostic health management (PHM) can be an effective solution for diagnosing failures, predicting residual lifetime, and estimating the reliability of assets [2]. PHM consists of sensing, diagnose, prognosis, and management stages. A key feature of PHM is its failure criteria. These failure criteria are determined by the physics-of-failure or sensing data trends.

The high accelerated limit test (HALT) is a method that identifies the weakness of systems such as electronic products [3]. In this test, severe temperature/vibration stresses beyond the specified operating limits are applied to the product. HALT can be used to provide threshold determination such as the operational limit and the destruct limit of products. IPC 9592A provides the requirements for HALT [4].

This paper reports on a study in which the failure modes of a small operational amplifier circuit board were investigated using HALT. First, failure mode and effect analysis (FMEA), which is a qualitative method to extract the typical failure modes of products, was applied to extract their potential failure modes and their effects before HALT. HALT was subsequently performed on an operational amplifier circuit board to investigate its potential failure modes.

2. Experimental procedure

2.1. Failure mode and effect analysis of operational amplifier circuit board

This section explains the FMEA procedure performed to extract potential failure modes and their effects before application of HALT. Fig. 1 presents a schematic of the operational amplifier circuit board used (Akizuki Denshi Tsusho Co., Ltd., AE-7368). The following test components were used: operational amplifier IC (TA7368), aluminum

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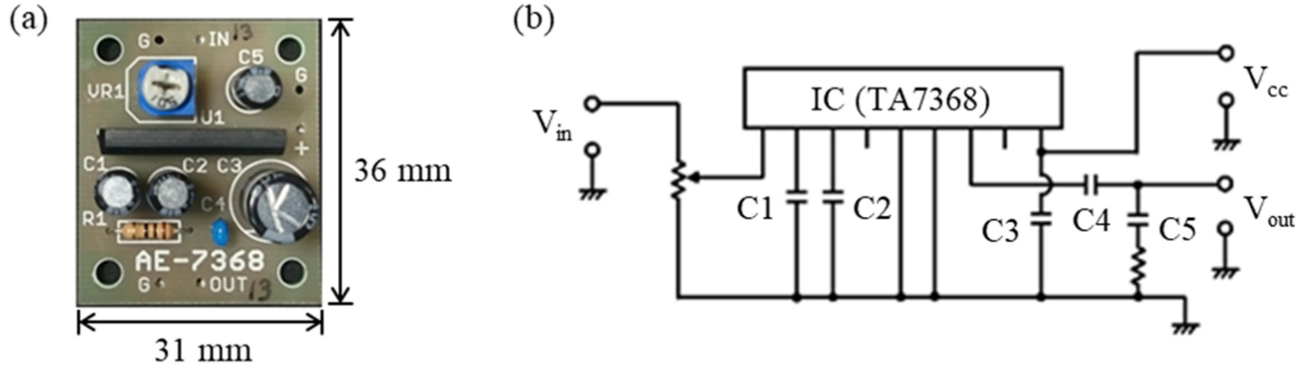

Fig. 1. The tested circuit board: (a) circuit board and components; (b) circuit diagram.

electrolytic capacitors (C1, C2, C3, and C5), ceramic capacitor (C4), and resistances (VR). These components were connected to the circuit board using tin-lead solder.

FMEA is a systematic method for identifying potential failure modes and prioritizing them. In this study, the failure modes of components were open circuit and short circuit [5,6]. Further, decreasing capacitance and increasing leakage current were also considered for capacitors. The effect of each failure mode was investigated per component using a breadboard before manufacture. Table 1 summarizes the results of FMEA for the small operational amplifier circuit components.

2.2. Test procedure for HALT chamber

In this study, eighteen circuit boards (No. 1 to No. 18) were prepared for HALT. Groups of three circuit boards were mounted on an aluminum plate (150 mm × 150 mm × 2 mm). Therefore, six specimen groups (A to F) were tested in several stress step recipes. A 10 V voltage collector was applied to each circuit using a power supply (Matsusada Precision Inc., PK-80). A 200 Hz sine wave with amplitude 0.6 V was generated as input voltage. Input and output voltages data acquisition was performed using LabView with a sampling rate of 5 S/s. The sine waveform during the HALT steps was captured every 10 s at a sampling rate of 10 kS/s. Fig. 2 shows examples of the output voltage (V_{out}), input voltage (V_{in}), and voltage collector (V_{cc}) at the sampling rates of 5 S/s and 10 kS/s.

Table 1
Failure modes and effect analysis of small operational amplifier circuit board components.

Component	ID	Failure mode	Anomaly of output voltage
Aluminum capacitor	C1	Open circuit	Decrease to 0 V
		Short circuit	No change
		Capacitance decrease	No change
		Increase in leakage current	Decrease slowly to 0 V
	C2	Open circuit	No amplitude with noise
		Short circuit	No amplitude
		Capacitance decrease	Amplitude reduction
		Increase in leakage current	Increase slowly to 5.0 V
	C3	Open circuit	No signal (0 V)
		Short circuit	Shift to 4.0 V
		Capacitance decrease	Amplitude reduction
		Increase in leakage current	Shift slowly to 4.0 V
	C5	Open circuit	Rectangular wave and noise
		Short circuit	No signal (0 V)
		Capacitance decrease	Rectangular wave and noise
		Increase in leakage current	No change
Ceramic capacitor	C4	Open circuit	No change
		Short circuit	Shift to 0 V
		Capacitance decrease	No change
		Increase in leakage current	Shift to 0 V
Trimmer potentiometer	VR	Open circuit (INPUT)	No amplitude
		Open circuit (GND)	Rectangular wave
		Short circuit (INPUT)	Rectangular wave
		Short circuit (GND)	No amplitude

The Qualmark Typhoon 2.5 HALT chamber, which provides controlled temperature and vibration to the product, was used in this study. The rapid temperature change rate (60 °C/min) and severe vibration tests were conducted with two test specimens fixed to a 762 mm^2 shaking table. Fig. 3 shows the setup of the specimens on the shaking table.

HALT can provide the following five kinds of stress tests to a specimen [6–8]:

1. Low temperature stress.
2. High temperature stress.
3. Vibration stress.
4. Thermal shock stress.
5. Combined temperature-vibration stresses.

Specimen groups A (No. 1, No. 2, No. 3) and C (No. 7, No. 8, No. 9) were tested in the low temperature stress test. The test started at 20 °C and the chamber temperature decreased by 10 °C until functional failure occurred. Specimen groups B (No. 4, No. 5, No. 6) and C were tested in the high temperature stress test. The chamber temperature was increased by 10 °C. Specimen group and D (No. 10, No. 11, No. 12) were tested in the vibration stress test. The vibration level was increased by 10 G_{rms} and its holding time, including transition time, was 10 min. Specimen group C was thus tested under low temperature/high temperature/vibration stresses. Comparing specimen groups A, B, C, and D, the effect of accumulated damage on product failure was examined. Specimen group E (No. 13, No. 14, No. 15) was evaluated for thermal shock stress. The test condition of thermal shock was determined by the results of low/high temperature stresses. Specimen group F (No. 16, No. 17, No. 18) was evaluated for combined temperature-vibration stress. The test condition was considered based on the result of the vibration stress step.

3. Results

3.1. Low temperature stress test

As temperature decreases, the amplitude of the output voltage of an amplifier becomes narrower. It is well-known that the electrostatic capacity of an aluminum electrolytic capacitor tends to decrease at low temperatures [9]. In this circuit board, the capacitor (C2) may affect the change in the amplitude of output voltage based on FMEA. The temperature in the chamber was decreased to −60 °C and the output waveform was seen to have a noise irregularity at −50 °C. Fig. 4 shows the noised wave of the output voltage at −50 °C. The output voltage fell at