Report 1 Destruction mechanisms resulting from vibration load in PCB-mounted electronics

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Temperature cycle testing and combined testing methods have been under study with regard to their effectiveness in evaluating soldered joints. However, there have been a variety of difficulties in quantifying destruction mechanisms that result from vibration load in PCB-mounted electronics, particularly in taking measurements in environments with a high level of vibration across a wide frequency range, such as in vehicle-mounted devices. In order to improve the accuracy of acceleration and simulation in the next generation of test methods, we must be able to quantify the mechanisms of destruction. This report will present methods of quantifying and clarifying failure modes that occur during the resonance vibration with the greatest increase in vibration stress for vehicle-mounted devices that endure high levels of vibration.

Introduction

The current proliferation of automotive PCB-mounted electronics includes such devices as electronic controls, car navigation systems, and ETC (electronic toll collection) that receive, transmit, and display information both inside and outside the vehicle.

Automotive PCB-mounted electronics are subjected to severe stress, including temperature, humidity, and vibration ^{1),2)}. Unlike ordinary electrical products, automotive parts are regularly subjected to vibration load, and so these parts must undergo vibration testing as a basis for acceptance. However, it is not currently clear what type of vibration load acts on the mounted parts and the mounting sections of PCBs, nor what mechanisms lead to their destruction.

The current progress of miniaturization in electronic mounting has led to a shift in electronic devices away from QFPs (quad flat pack IC packages) to BGAs (ball grid arrays) and CSPs (chip scale packages). In this newer construction, more mechanical stress can directly affect the mounted sections. Also, the shift away from using conventional Sn-Pb eutectic solder in favor of lead-free Sn-Ag-Cu solder on the mounted parts is well under way, and the test standards for reliability are not yet clearly defined ³.

The research on vibration load done for this report proposes to clarify, based on experiments, what kind of stress leads to the destruction of the mounting sections of PCBs with mounted electronics. This research further proposes to indicate the significance of vibration test methods and suggest the crucial points in vibration testing.

2 Test method

2-1 Test specimens

For this research, we selected PCBs mounted with QFP packages from among generally used electronic parts for vibration tests. These packages can be expected to incur the greatest load on the mounted sections.

The mounting PCBs, as shown in Fig.1, were glass epoxy circuit boards (FR4 100 mm x 100 mm x 1.6 mm) containing two mounted QFP packages (240 pin, 0.5 mm pitch; and, 112 pin, 0.65 mm pitch). Sn-3.5Ag-0.75Cu solder was used for mounting. Peak mounting temperature was 240 , which is the solder material melting point plus 20 . Thermocouples were used to measure the mounting temperature at five points (3 points on the soldered sections, 1 point on the PCB surface, and 1 point on the package surface), and reflow oven temperature settings were adjusted so that the QFP mounting sections reached the prescribed temperature. The temperature profile was created with the aim of maintaining temperature at a minimum of 220 for at least 30 seconds at the areas to be heated, and maintaining the preheating section at 170 for not more than 90 seconds.

2-2 Test method

Fig.2 shows the installation and attachment of the mounting PCB shown in Fig.1 to the combined environment test system (Manufactured by Espec: EVS08-10-10, vibration force: 10 kN, max. acceleration: 909 m/s², max. displacement: 51 mmp-p, range of vibration frequency: 3 to 2000 Hz). The PCB was perforated in four places to accommodate bolts for attaching the PCB to a rigid aluminum jig that was fastened to the vibrating machine. To provide uniform fastening force, the tightening torque was standardized at 1.17 N \cdot cm (12 Kgf \cdot cm). This tightening torque was found in preliminary experiments to produce stable PCB vibration characteristics.

The direction of vibration was along the z axis. Spacers were placed between the PCB and the jig at the four fastening perforations to allow the mounting PCB to flex.

During the vibration tests, the vibration characteristics of the mounting PCB were measured using laser displacement meters (manufactured by the Keyence Corporation) with 0.1 μ m resolution to measure PCB displacement, and acceleration pickups (manufactured by Yamaichi Electronics Co., Ltd.: model 107S, sensitivity 0.039 m/s², max. acceleration: 10,000 m/s², frequency range: 1 to 20 kHz, dimensions: 4.6 x 5.8 mm, weight: 0.5g) to measure acceleration. To minimize as much as possible the affect the acceleration pickups had on the tests, devices weighing a mere 0.5 g were used.

Vibration mode of the QFP leads was observed during testing with a high-speed digital C-MOS/PCI MotionPro camera (manufactured by Redlake MASD, Inc.). The tests were shot at 1,000 to 2,000 frames per second.



The vibration stress applied in these experiments was within the range used in vehiclemounted devices, from 9.8 m/s² (1 G) to 39.2 m/s² (4 Gs).

3 Resonance surveys and resonance frequency ranges in endurance test results

To find the resonance frequencies of the mounting PCBs used in these experiments, resonance surveys (results in Fig.3) were performed according to the resonance test conditions shown in Table 1. As these results show, the resonance frequencies detected were 353 Hz, with an acceleration of 1073 m/s², as well as resonance frequencies of 630 Hz and 890 Hz.

We selected the primary natural frequency with the greatest displacement.

Considering that resonance frequency might vary during the tests, endurance tests were performed using a range sweep of ± 5 Hz centered on the resonance frequency.

Table 2 shows endurance test conditions.

Frequency	100 to 1000 Hz
Acceleration	9.8 m/s² (1G)
Control point	Aluminum plate
Sweep time	10 minutes

Table 1 Vibration conditions (resonance survey)

Table 2 Vibration conditions (endura	ance test)
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Frequency	348 to 358 Hz
Acceleration	9.8 m/s² (1G)
Control point	Aluminum plate
Sweep time	10 minutes
Test time	48 hours





Forty-eight hours after beginning the endurance test, rupture of the QFP leads was observed. Photo 1 shows the lead rupture as seen on the high-speed camera. These results indicate that rupturing began with the first pin from the QFP corner section, then continued in succession with the second pin followed by the third pin. Despite movement being initiated by vibration applied along the z axis, the leads were observed to exhibit torsional vibration. Post-test observation confirmed that the origin of the vibration was biased toward the side surface of the QFP shown in Photo 1.

From these results, we can hypothesize that other stress is also being applied in addition to the vibration stress along the z axis applied to the QFP leads, and that differing vibration characteristics are generated on the mounting PCB.



Photo 1 Ruptured leads (endurance test)

4 Measuring PCB displacement

The load on parts in the mounting PCBs used in vibration tests originates in vibration coming from the PCBs. Therefore, in order to grasp the measurement functions of the acceleration pickups used in these measurements and to identify the vibration of the mounting PCBs, we measured displacement motion for both PCBs with no parts attached and PCBs with two QFP packages attached. Fig.4 and 5 show the results.

First, the resonance frequency survey was measured with the acceleration pickup and the laser displacement meter. The resonance frequency survey results from the acceleration pickup measurements were 396 Hz, and the laser displacement meter measurements were 410 Hz, an approximate difference of 14 Hz.

This difference presumably originates from the weight of the acceleration pickups and from the restraining effect of fastening the acceleration pickups to the PCBs. Roughly equivalent values were obtained by converting between the acceleration and displacement measurements obtained, thus confirming the validity of the measurements from these sensors. For resonance vibration, Fig.4 and 5 show the results obtained by measuring the PCB vibration with the laser displacement meter.

These measurements, shown in Fig.4 (a) and Fig.5 (a), were taken at 5 mm intervals on the PCBs. These results show that when acceleration vibration of 9.8 m/s^2 is applied, at that resonance frequency PCB displacement is 0.25 mm at the center of the PCB.

Also, the displacement at the y = 0 point in both Fig.4 (b) and Fig.5 (b) indicates that the restraint from mounting parts results in smaller displacement measurements.



PCB displacement from resonance (without mountings)



5 Differences in vibration characteristics of PCBs and parts

PCB-mounted QFPs are designed so that the packages are linked to the PCB by leads that contain a certain spring constant, and vibration is transmitted through these springs. As a result, there is a variation between the vibration acceleration of the parts and the vibration acceleration of the PCB, as Fig.6 shows.

If:

(t) = the vibration acceleration of the PCB, (t) = the vibration acceleration of the parts, m_1 = the mass of the PCB, m_2 = the mass of the parts, and F = the force acting on the leads serving as linkage. Then: $F = m_1$ (t) - m_2 (t) $= m_1$ max sin(w t+ 1)- m_2 max sin(w t+ 2) (1).

This indicates that the differences in acceleration and phase have a major impact on the force acting on the leads that link the parts to the PCB.



Fig.6 Acceleration of PCB and parts during vibration tests

Fig.7 shows the differences in acceleration measurements at the center of the PCB and at the center of the QFP. We collected data on (1) vibration applied to the PCBs as well as actual vibration on the PCBs, and (2) vibration applied to the QFPs as well as actual vibration on the QFPs. Taking the applied vibration, which was common to both, as standard, we graphed the vibration occurring on the PCBs and on the QFPs.





To confirm the amount of phase and acceleration difference resulting from the position on the PCB, we searched in close proximity to the QFP for phase difference t and acceleration difference (20 \log_{10} B/A) between the QFP and the PCB. Fig.8 shows the results. The vibration was applied on the z axis in close proximity to the resonance frequency. The acceleration measurements at this time included measurements for each of the x, y, and z axes, with results calculated for each. The lines shown in the graphs represent the maximum acceleration (displacement) frequencies reached (resonance frequency) for each location, and so the nine graphs in Fig.9 (a-1) to (c-3) show the acceleration variation for the frequencies on each axis (x, y, and z). From these results, we find the variation in acceleration differences between the PCB and the QFP shown in the final three graphs, Fig.9 (a-4, b-4, and c-4).

As can be seen from Fig.8, a certain amount of difference exists, and the phase difference becomes greater in closer proximity to the resonance frequency. Also, depending on the location, the phase difference is greater on the different axes of vibration: to the right of the QFP (near the center of the PCB) for the vibration on the y axis the gain difference is 10 dB and the phase difference is -150 °, while to the left of the QFP (near the edge of the PCB) for the vibration on the x axis the gain difference is 28 dB and the phase difference is -150 °.



Fig.8 Measurements of acceleration and phase differences between PCB and QFP

The greatest acceleration occurs in the vibration along the z axis. This can be seen from the time variation of the acceleration in the resonance frequencies along with the time variation of the acceleration difference between the PCB and the QFP as shown in Fig.9. The acceleration along the x and y axes is less than one tenth that of the z axis, but we find that the acceleration difference is greater in close proximity to the leads at (a) and (c). In particular, the QFP location near the edge of the PCB shown in Fig.9 (a) exhibits an acceleration difference on the x axis of 200 m/s², which is greater than other locations. Observation with the high speed camera confirmed that this phenomenon corresponded to torsional vibration and also to rupture onset locations. In the results shown in (b) for measurements taken at the center of the PCB and at the center of the QFP, uniform acceleration was seen on all three axes, and no major difference was observed between the acceleration on the PCB and the QFP.





6 Conclusion

Using a high-speed camera, we monitored vibration load in PCB-mounted electronics. We examined lead rupturing in regard to vibration load by identifying distortion behavior and rupturing in QFP leads, and by measuring the vibration characteristics of parts and PCBs. Our main conclusions are as follows.

- (1) Observation of lead rupturing with a high-speed camera showed that the QFP leads became twisted as they vibrated. Rupturing began from the first lead on the QFP corner and then continued with the neighboring leads in succession.
- (2) The displacement accompanying PCB vibration was greater from the fastening points toward the center of the PCB, with curvature occurring between fastening points. We confirmed that restraint due to mounting parts reduced the vibration displacement of the PCB.
- (3) We confirmed that in proximity to the resonance frequency the greatest acceleration gain difference and phase difference on the parts (QFP) and on the PCB occurred in close proximity to the linkage points of the parts.
- (4) Little variation was seen in the scale of individual vibrations on the QFP mounted section, but increased PCB and QFP acceleration and phase difference were seen in proximity to the leads near the edge of the PCB. Also, the cross-directional x axis acceleration difference increased in response to the z axis load, causing twisting to occur. This torsion is believed to have caused the initial rupturing.

[Bibliography]

- Society of Automotive Engineers of Japan, Inc., "Automotive Engineers HAND Book," 1990
- 2) Nishi, "Vehicle electronics and reliability," Electronics Parts and Materials No.5, 1979
- Yuichi Aoki, Hirokazu Tanaka and Toshiyuki Hamano, "Investigation of method of evaluating solder joints by combined environmental test," The 15th JIEP Annual Meeting, p.183-184, 2001