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Acoustic noise and vibration analysis of solid state drive induced by multi-layer ceramic capacitors

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ABSTRACT

Solid-state drives (SSDs), popular information storage devices, are typical printed circuit board assemblies (PCBA). As is true of other PCBAs, SSDs feature many multilayer ceramic capacitors (MLCCs). SSD vibration accompanied by high-pitched noise reflects the piezoelectric properties of MLCCs, and may cause great inconvenience to users. Here, we developed a finite element (FE) model predicting the vibration of the substrate associated with SSD acoustic noise. Because the SSD structure is complex and the model must be valid in the audible frequency range, we systematically constructed the model that is performed modal analysis. The excitation sources of the MLCCs were also modeled from a piezoelectric viewpoint, in which vibration analysis was performed in conjunction with the SSD model. Finally, the FE model was verified by comparing predicted and actual vibrations of an operational SSD.

1. Introduction

Recently, solid-state drives (SSDs) that store information on flash memory chips both very rapidly and very stably have become popular. As SSDs store information as electronic charges, no moving parts are involved, unlike hard disk drives (HDDs). It is well-known that HDD disk rotation is associated with vibration and noise issues. SSDs have fewer such problems; however, high-pitched noise can be generated by multilayer ceramic capacitors (MLCCs) mounted on SSDs [1].

SSDs are typical printed circuit board assemblies (PCBAs), bearing packages, chips, and many active and passive elements. MLCCs are the major passive elements; these are highly integrated capacitors essential for stable SSD operation. The principal MLCC material, $BaTiO_3$ (BT), exhibits high-level permittivity but also piezoelectric features. Thus, when an alternating current (AC) voltage is applied, the MLCC surface repeatedly shrinks and expands [2]. When MLCC vibration is transmitted to the substrate via solder, the substrate may resonate, creating noise. Previous studies have reported the association between MLCC vibration and noise [3]. This noise is extremely disturbing because it is of high frequency and can greatly inconvenience nearby users of electronic devices (e.g., mobile phones, laptops, and other SSDs). As technology improves, MLCCs on PCBs become more densely packed, increasing SSD vibration and noise.

Many studies have dynamically analyzed PCBAs; most were drop-impact works. An analytical model predicting PCBA drop reliability is available [4], as is a transient dynamic simulation for mobile phone PCBs in terms of drop-impact [5], and a modeled simulation of drop-impact analysis of multilayered PCBs [6]. Vibration analyses of PCBAs have focused principally on fatigue failure or cracking of solder caused by external vibrations [7,8]. Some finite element (FE) models for multilayer PCBs, and simplifications thereof, are available [9,10]. However, these studies did not address PCBA vibration per se, and did not evaluate acoustic noise. Also, previous studies did not examine the latest products; the PCBs evaluated were simpler than those in current use. In addition, the impact and external vibration analyses covered frequency bands much lower than the audible band (20–20,000 Hz). Thus, our present vibration analysis seeks to deal with PCBA noise problems. We built an FE model for products including MLCCs as sources of vibration.

We performed FE analysis of an SSD, unlike any previous study. As SSDs are very small and complex, systematic application and appropriate simplification are required during FE modeling, especially that of PCBs containing SSDs. We derived the mechanical properties of PCB layers applying the rule and inverse rule of mixtures; detailed copper patterns of PCBs were not required. Thus, high-frequency modes could be verified in terms of their isotropic properties. In addition, MLCCs causing vibration and noise were modeled when various voltages were input, improving the analysis accuracy. We thus constructed simplified FE models of SSDs of the M.2 form and MLCCs. Vibration analysis was performed by coupling SSDs and MLCCs. The FE model was verified by comparing the predicted vibration response with actual vibrations and noise under various conditions.

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2. SSD vibration analysis

2.1. Acoustic noise-generating mechanism of SSDs

An MLCC consists of an internal electrode, a BT dielectric, and an external electrode. When an electric field is applied to the dielectric layer, the layer becomes deformed due to the piezoelectric properties of BT, which has a high dielectric constant but is also a typical ceramic in terms of exhibiting a piezoelectric effect. As the BT density is very high in MLCCs, the piezoelectric effect and the associated oscillations are large when an AC voltage is applied. However, as MLCCs are very small, the amplitudes are small, and the natural frequencies of MLCCs are higher than the audible frequency range. Thus, the acoustic noise problem is not attributable to MLCC vibration. Audible noise is produced if the MLCC is mounted on the PCB in a position allowing resonation with the PCB. In addition, the PCB must be sufficiently large to produce vibrations of perceptible amplitude. If these conditions are satisfied, then an excitation force transferred to the substrate resonates the PCB and generates acoustic noise. SSDs satisfy the above conditions; the MLCCs trigger high-pitched noise [1]. Thus, the SSD model must consider situations in which the PCB is excited and expresses acoustic noise during SSD operation. Fig. 1 shows how acoustic noise is generated. When verifying our analysis, our target frequency band was the audible frequency range of 20–20,000 Hz. Fig. 2 outlines the SSD used in this study. It is the M.2 standard and 80 mm × 22 mm in size, and MLCCs that operate as the source of vibration are represented also. The MLCCs mainly causing acoustic noise are located near the power management integrated circuit (PMIC) that serves as the power supply and are nine 1005-size MLCCs and one 1608-size MLCC. And these 10 MLCCs excite the substrate to generate vibration and acoustic noise.

2.2. Modal tests for SSD

Modal tests were performed in three steps. The first step evaluates a bare PCB (thus in the mechanically free state). The second step evaluates the SSD in the mechanically free state. The final step evaluates the SSD connected to an adapter. The reasons for these experiments are to analyze the vibration characteristics of the bare PCB itself and SSD itself, and to eliminate the uncertainty of boundary conditions. In other words, in order to analyze a complex object, the experiment was conducted from a simple object to increase the accuracy. For modal testing in the mechanically free state, an impact hammer is used to excite the PCB. Thus, the first two steps feature impact testing. The specimens were placed on soft sponges to mimic mechanically free conditions. Since the stiffness of the sponge is very low compared to the stiffness of the specimens, the test result shows that the first natural frequencies of the specimens were more than 10 times the rigid body motion frequencies, and it shows this experimental set-up was suitable for free-free modal tests. The measurement tools included an accelerometer measuring responses and an impact hammer for excitation; an LMS SCADAS (Siemens) was used to acquire responses. The number of nodes measured in steps 1 and 2 were both 21. To verify reproducibility, the mean values of responses to five excitations were obtained. As impact testing is performed manually, the frequency range is narrow in comparison with that of the audible frequency. The responses of the two experiments ranged from 0.1–6.4 kHz when 12 modes of the bare PCB and 7 modes of the free SSD were evaluated.

However, our purpose was to construct an SSD model predicting vibrational behavior in the audible frequency range. Therefore, the final step was performed using a shaker and a laser Doppler vibrometer (LDV; Polytec). The SSD was connected to an adapter, and the adapter to a jig excited by the shaker. The LDV measured the velocity of each SSD node. We placed the setup on a vibrationally isolated table to eliminate external mechanical noise, and the jig was designed to avoid resonance under 20 kHz. We obtained data from 161 nodes, and, because measurements were made at relatively high frequencies, the mean values of responses to 20 excitations were obtained. All responses of 23 modes were in the audible frequency range. Fig. 3(a) shows the experimental setup for analysis of bare PCBs and SSDs; Fig. 3(b) shows that for fixed SSD assessment.

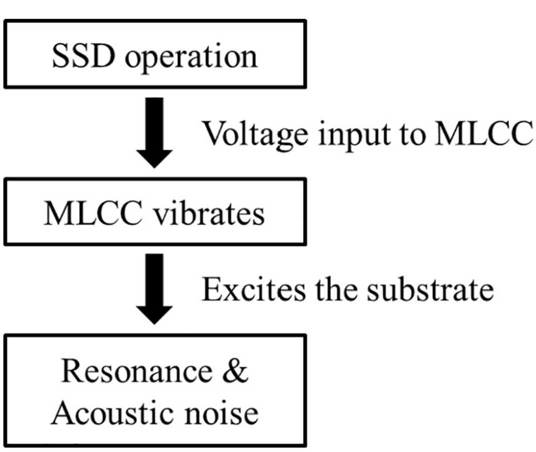

Fig. 1. The process of the acoustic noise generated in the SSD.

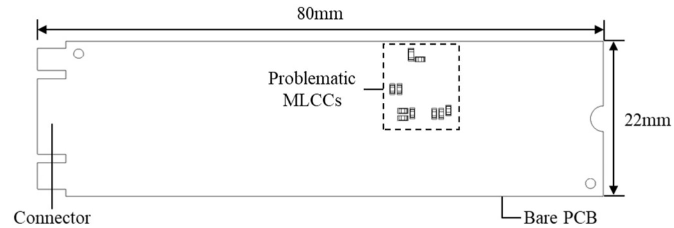

Fig. 2. The schematic drawing of the M.2 SSD and the problematic MLCCs.

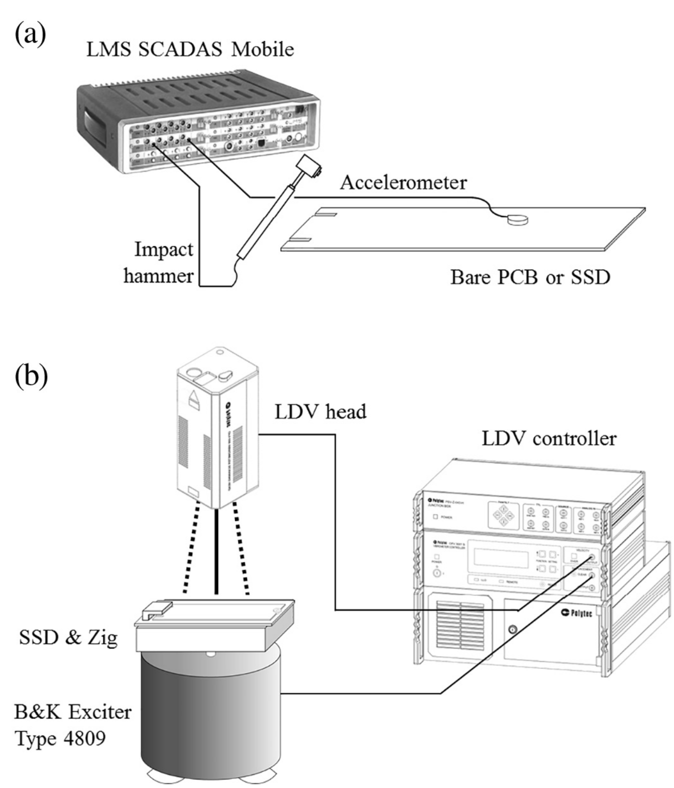

Fig. 3. Experimental setups for modal test: a) bare PCB and SSD, b) SSD connected to an adaptor.