The effect of the PCB motion on the dynamic response of MEMS devices under mechanical shock loads

Fadi M. Al Saleem, Mohammad I Younis, and Mahmoud Ibrahim
Department of Mechanical Engineering, State University of New York at Binghamton,
Binghamton, NY 13902

ABSTRACT
In this work, we present a theoretical and experimental investigation into the effect of the motion of a printed circuit board (PCB) on the response of MEMS devices to shock loading. For the theoretical part, a two-degrees-of-freedom model is used, where the first-degree-of-freedom accounts for the PCB. The second-degree-of-freedom represents the motion of the MEMS microstructure, such as a beam or a plate. Acceleration pulses are applied to the MEMS-PCB assembly base (such as those generated from a drop table test). Simulation data are presented to show the effects of the natural frequency of the PCB, the natural frequency of the microstructure, and the shock pulse duration. Universal 3-D spectra representing the effect of these parameters are presented. These spectra can help MEMS designers ensure safe operation of their MEMS devices. It is found that neglecting the PCB effect on the design of MEMS devices under shock loads can lead to undesirable motion of their microstructures. An experimental investigation is conducted to verify the theoretical results using a capacitive accelerometer. Experimental data for the response of the accelerometer while it is mounted on two representative PCBs due to different base shock load conditions are shown. It is found that these data are in good agreement with the simulation results.

1. Introduction
The reliability of MEMS devices in shock environment represents one of the key factors for the growth of their industry and the increase in their commercialization [1, 2]. Unlike the macro scale devices, where the failure is primarily due to fatigue, mechanical shock loads in micro scale systems can cause different failure mechanisms such as mechanical failure, stiction and short circuit. In commercial devices and electronics, MEMS devices are placed on a PCB to facilitate the electrical interconnections and the structural support [3-5]. MEMS microstructures, prior to getting assembled on a PCB, are housed in a mold compound which can be for example ceramic or plastic. However recently, in some MEMS applications, such as RF MEMS switches [6] and low g accelerometers [7], the MEMS device is directly placed on the PCB in order to reduce the system complexity and cost. Mounting the microstructure of a MEMS device (directly or within the mold compound) on a PCB may raise concern about the role of the PCB in amplifying the shock effects on the microstructure and distorting its sensing/actuating signal. This is particularly important in applications such as micro-g-accelerometer where very high sensitivity to motion is required [7].

Figure 1 shows the assembly (packaging) levels of a typical MEMS device [3-5]. As seen from the figure, four levels of assembly can be identified. These represent the connection between a microstructure and a substrate, the bonding between the substrate and the chip, the connection of the leads from the chip carrier to the PCB, and the connection of the PCB to the supported structure. These four connections are almost rigid to ensure undistorted signal from the microstructure while sensing or actuating. However, because the microstructure and the PCB are flexible structures (beams, plates, diaphragm), the interaction of their motion can be significant. Therefore, whether a microstructure is attached directly to a PCB like in [6, 7] or is packaged in a standard assembly process as in Figure 1 the interaction of its motion with the PCB should be analyzed.
The current trend in the IC and MEMS industry is to make the PCB very thin and flexible. This means that the PCB is now more susceptible to experience considerable bending motion when subjected to mechanical shock and vibration. This motion can be transmitted to the microstructure leading to either its collapse or false function. These new PCBs are characterized by having low natural frequencies. A coupling in the response between such PCBs with MEMS devices that have low natural frequencies, such as microcantilever beams, may occur. On the other hand, thick or small PCBs of high natural frequency are expected to cause the coupling problems with stiffer microstructure, such as clamped-clamped microbeams and pre-stressed diaphragms.

Many authors have studied the MEMS response under shock loads without incorporating the PCB effects [1], [9-15]. Some of this works are reviewed in [15]. The response of MEMS devices to shock loads including the PCB (assembly) effects has not investigated thoroughly. Gogoi et al. for example, [16] remarked that the fundamental frequency of the system represented by the chip attached to the PCB should lie outside the intended operating frequency range of the MEMS structure. Fan et al. [3] evaluated the response of a microstructure used for acceleration measurement under severe shock loads. They indicated that the PCB, on which the microstructure is mounted, introduces undesirable effects on the acceleration measurements. To alleviate this factor, they proposed to stiffen the PCB.

Srikar et al. [2] studied the reliability of MEMS devices subjected to shock loads. They indicated that most MEMS devices experience the shock loads as quasi-static loads since their natural periods are much smaller than the duration of the shock loads. Srikar et al. [2] pointed out that the package reduces the shock load applied to the microstructure and the worst-case scenario is to transfer this shock pulse without significantly alter its shape or intensity.

In a previous work [17], the mechanical shock was modeled as a single point force impacting the PCB at which the MEMS device is mounted. Simulation results were presented to show the effects of the fundamental natural frequency of the PCB, damping, shock pulse duration, electrostatic force, and their interactions on the MEMS response. In [18], a continuous-lumped mass model was used to simulate the PCB-MEMS assembly response under the effect of a point force impacting the PCB. In [19] we studied theoretically and experimentally the response of a capacitive accelerometer MEMS device under the combined effects of shock and electrostatic force. In this work, we model the mechanical shock as a base excitation acceleration pulse affecting the PCB-MEMS assembly, which is an accurate way to model shock pulses due to drop-table or drop tests [20]. Further, experimental results that compare the responses of a capacitive accelerometer while it is mounted over different PCB designs are shown for different base excitation shock load conditions.

2. Problem formulations

As mentioned above, we assume here that both the substrate-chip and the chip-PCB assembly to be rigidly connected [2], [21]. Hence, the assembly effect reduces to that of the PCB motion only. We use a 2-DOF model, Figure 2a, to study the PCB effect on the response of a MEMS device under shock load. The first DOF accounts for the PCB motion and the second DOF represents the motion of the microstructure, such as a beam or a plate, which is mounted over the PCB. Shown in Figure 2 are $k_m$: microstructure stiffness, $k_{PC}$: PCB stiffness, $c_m$: microstructure damping, $c_{PC}$: PCB damping, $m_m$: microstructure mass and $m_{PC}$: PCB mass.

![Figure 1: Schematic of a typical MEMS device mounted to a printed circuit board.](image-url)
Base shock force is a typical example for the shock forces that might affect the response of a 2-DOF structure [22], similar to the case for the MEMS-PCB assembly. Base (ground) shock occurs when the base of the assembly undergoes a sudden acceleration change (Figure 2.a). This change happens, for example, due to the drop of the assembly to the ground or due to a drop table test. To evaluate the microstructure response under shock due to drop test, it is assumed that the shock has a shape of a sine pulse of period $T$, Figure 2.b, which represents a good representation for a shock pulse [20],[23]. Under this assumption, the governing equations of the system are given by

$$m_{m} x''_{1} + k_{m} (x_{1} - x_{2}) + c_{m} (x'_{1} - x'_{2}) = 0$$  \hspace{0.5cm} (1)  

$$m_{p} x''_{2} - k_{m} (x_{1} - x_{2}) - c_{m} (x'_{1} - x'_{2}) + k_{PC} x_{2} + c_{PC} x'_{2} = k_{PC} y + c_{PC} y'$$  \hspace{0.5cm} (2)  

where $y$ and $y'$ are the displacement and the velocity of the assembly base, respectively. The base acceleration $y''$ is assumed to be a half sine of amplitude $A_o$: $y'' = A_o [\sin(\omega_{\text{Pulse}} t) u(t) + \sin(\omega_{\text{Pulse}} (t - T)) u(t - T)]$, where $\omega_{\text{Pulse}}$ is the shock pulse frequency, $t$ is time, and $u(t)$ is the unit step function. Then to get $y$ and $y'$, $y''$ is integrated twice and once with time, respectively.

![Figure 2: Schematics (a) for the MEMS-PCB assembly subjected to a base acceleration due to drop table test, (b) for a half-sine pulse used to model actual base shock acceleration.](image)

3. Simulation results

In this section, simulation data that show the effects of the fundamental natural frequency of the PCB, the natural frequency of the microstructure, and the shock pulse duration are presented. These simulation results were obtained by solving equations (1-2) using modal analysis. Figures 3a and 3b show the maximum relative amplitude of a microstructure with respect to the PCB $(x_{1}, x_{2})$ that has a fundamental natural frequency 24 kHz (MEMS Omni-directional pressure microphone [25]). The response on this figure and all subsequent ones is normalized with respect to the static deflection of the microstructure to an equivalent static load. Results are shown for different PCB natural frequencies $\omega_p$ with $T = 1.0 \text{ ms}$ and $T = 60\mu\text{s}$. In all figures, the damping ratio is assumed to be zero, considering the worst case scenario for a shock response, unless stated otherwise. The figures show that the MEMS response is always amplified due to the presence of the PCB except for the zone where the natural frequency of the PCB is very low (the response is attenuated) and very high (the response is the same as if there is no PCB). Moreover, as the shock duration value decreases the amplification amplitude increases.

Next we show in Figure 4 a universal 3-D plot for the normalized deflection for a microstructure as a function of the shock, the PCB natural frequency, and the natural frequency of the microstructure for light damping case (damping ratio $\xi$ is assumed to be 0.05). This plot can serve as a guideline for a MEMS designer to ensure reliable operation of their various MEMS devices on a chip. For example the pressure microphone has a natural frequency of 24 kHz. The shock duration that this microstructure could suffer from in a real application due to the
drop in the ground is between $0.1\text{ms} -1.0\text{ms}$, corresponds to $\omega_{\text{MEMS}} / \omega_{\text{Pulse}} = 2.4-24$ (the bounded surface between the two lines in Figure 4). Based on Figure 4, the designer could select the suitable PCB that has the minimum effect on amplifying the unwanted response of the microphone due to shock load.

![Image](image1.png)

(a) $T=1.0\text{ms}$  
(b) $T=60\mu\text{s}$

**Figure 3:** The microstructure maximum response to base shock load.

4. Case study characterization: experiment and simulation

This section presents an experimental and theoretical investigation for the responses of a capacitive accelerometer, including the PCB effects, due to base shock loads. Two PCBs of representative fundamental natural frequencies were chosen. The first is a circular one of natural frequency that is very large compared to the natural frequency of the accelerometer (PCB1) (Figure 5a). The other is a rectangular one with a natural frequency close to the natural frequency of the accelerometer (PCB2) (Figure 5b). The second PCB is designed to adhere to the JEDEC [26] standard for electronics component shock testing.

We began our experimental investigation by first characterizing the two PCBs responses. To accomplish this, the two PCBs were mounted on the head of a shaker. A laser vibrometer was used to monitor the velocity response of each PCB. A reference accelerometer was mounted on the head of the shaker to measure its acceleration. A random noise voltage was applied as an input to the electromagnetic shaker to obtain the frequency response of the two PCBs. Figure 6 shows, as an example, the obtained frequency response and the corresponding mode shape of PCB1 at its first fundamental natural frequency. The figure shows that PCB1 has a first natural frequency around $6.0\ kHz$. Similarly, PCB2 was tested and found to have a fundamental natural frequency of $230\ Hz$.

![Image](image2.png)

**Figure 4:** A universal 3-D plot of the normalized relative amplitude of a microstructure for different $\omega_p$ and $\omega_{\text{Pulse}}$ values for the case of $\zeta=0.05$. 
A commercial off-the-shelf capacitive accelerometer fabricated by Sensata Technologies [27], was used for our experimental investigation (Figure 7a). The accelerometer is made up of an alloy 42 cantilever beam of thickness 150 microns with a proof mass (approximately of length =9mm and width= 5.32 mm) attached to its tip. The proof mass forms one side of the capacitive electrode used for detection. The separation between the stationary electrode and the proof mass is 50.8µm. The natural frequency of the device was obtained to be 187 Hz and the damping ratio is 0.5. The device was mounted on PCB1 and latter on PCB2. Then, the accelerometer-PCB assembly was mounted over the head of a shaker. A laser vibrometer was used to monitor the motion response of the accelerometer. A reference accelerometer was mounted on the head of the shaker to measure its acceleration. Figure 7b shows the experimental set used for this investigation.

![Image](image.png)

**Figure 5:** A picture for the PCBs used for testing

![Image](image.png)

**Figure 6:** (a) Frequency response of PCB1, (b) a 3D plot for the first mode shape of PCB1, which was obtained experimentally by measuring the PCB response at different locations using the laser vibrometer. The figure shows that the PCB moves purely up and down at this mode.

**Experimental data and comparison with simulation results**

First, the response of the capacitive accelerometer was obtained. Toward this, the capacitive accelerometer was mounted directly on the top of the shaker (without a PCB), and its response was monitored. Two displacement measurements were obtained using the laser vibrometer, one for the absolute motion of the accelerometer and
the other for the substrate motion, which is the same as the PCB motion; assuming a rigid connection between the PCB and the accelerometer substrate. By subtracting these two measurements, the relative displacement of the diaphragm relative to the substrate (PCB) was obtained. Figure 8.a shows the normalized maximum response of the accelerometer for different shock load time durations while it is not mounted over PCB1 (shock spectrum). In this figure, the experimental data are compared with S-DOF shock spectrum. The figure shows a good agreement between simulation and experimental results.

Next, the accelerometer was mounted over PCB1, shown in Figure 5a. The PCB was fixed using four screws to the head of the shaker. Since the ratio of the PCB natural frequency to the accelerometer natural frequency is very high \( \omega_p / \omega_{MEMS} = 6kHz / 187 Hz = 32 \), it is expected, according to Figures 3 and 4 in section 3, that the PCB will transfer the shock load to the accelerometer microstructure without any alteration. Figure 8b compares simulation and experimental results for the maximum normalized relative amplitude of the tested accelerometer for different shock duration values when the accelerometer is mounted on the PCB. A comparison between Figure 8a and Figure 8b shows that the shock spectra of the two cases are similar. This agrees with our conclusion in section 3; that for a base shock load, as the ratio between the natural frequencies of a PCB and a MEMS device increases the PCB will transfer the shock load to the MEMS device without alteration (i.e. the shock spectrum of the MEMS device when its mounted over a PCB should be similar to the one when the MEMS is not).

Next, the accelerometer was mounted over PCB2. The ratio of the natural frequency of PCB2 to the accelerometer natural frequency is 1.23. Figure 4 in section 3 indicates that a high amplification for the MEMS response occurs at this ratio. However, since the damping ratio of the accelerometer is very high (0.5 compared to 0.05 in Figure 4), we expect less amplification. Figure 9.a compares simulation and experimental results for the maximum normalized relative amplitude of the tested accelerometer for different shock duration values when the accelerometer is mounted on PCB2. This figure shows a good agreement between simulation and experimental results. A comparison between Figure 8.a and Figure 9.a shows that at this specific PCB/MEMS natural frequency ratio, the response of the microstructure is amplified. This happened because the natural frequency of the PCB is near that of the microstructure.

Figure 9.b shows a sample of the microstructure transit response with PCB2 (dynamic response amplified) and without PCB2 (quasi-static response with no amplification), due to shock loads of \( T = 5.0 \) ms. This figure shows clearly that a MEMS device, even with a high damping ratio, which is expected to respond quasi-statically to shock load may respond dynamically to the same shock load because of a poor design of the PCB.

**Figure 7:** (a) A picture for a taken-apart capacitive accelerometer, fabricated by Sensata Technologies [27], (b) schematic for the experimental setup and the data acquisition system.
5. Conclusion and summary

We investigated the response of MEMS devices including the effect of the PCB motion for different conditions of the base motion shock. It was found that neglecting the PCB effect on the modeling of the microstructure of a MEMS device can underestimate the microstructure motion. A universal 3-D plots accounting for the natural frequency of the PCB, the natural frequency of the microstructure, and the shock duration are used to define the amplification zones in which the normalized response of a microstructure will be amplified. Such plots can be used by MEMS designers to help ensure safe operation of their MEMS devices. An experimental investigation has been conducted to characterize a capacitive accelerometer that is mounted over a PCB. Experimental results for the capacitive accelerometer when it is mounted on two different PCBs due to different base shock load conditions are shown. It is found that these results are in good agreement with what we predict using simulation.
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7. References
[27] www.sensata.com